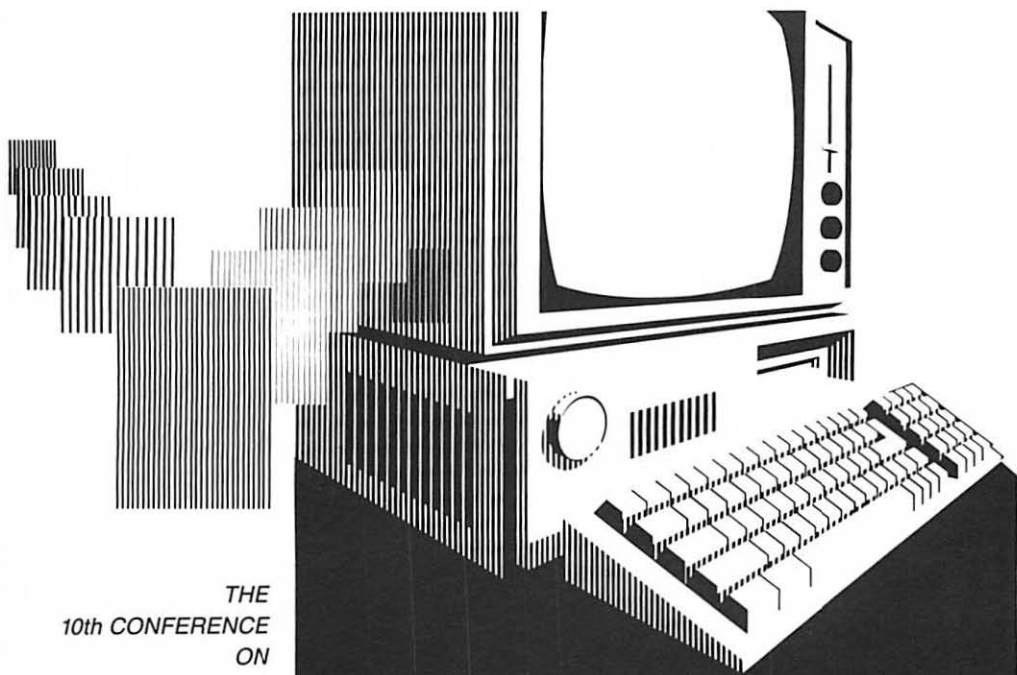




THE
10th CONFERENCE
ON
**COMPUTER
APPLICATIONS
IN
RADIOLOGY**
AND
4th CONFERENCE
ON
**COMPUTER
ASSISTED
RADIOLOGY**

ANAHEIM
CALIFORNIA
June 13-16, 1990

SCAR 90

**COMPUTER
APPLICATIONS
TO
ASSIST
RADIOLOGY**

SCAR 90

COMPUTER APPLICATIONS TO ASSIST RADIOLOGY

Edited by

Ronald L. Arenson, M.D.

*Professor of Radiology
University of Pennsylvania School of Medicine
Associate Chairman (Clinical Services)
Department of Radiology
Hospital of the University of Pennsylvania
Philadelphia, PA*

Richard M. Friedenberg, M.D.

*Professor and Chairman
Department of Radiological Sciences
University of California, Irvine
Orange, CA*

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INTRODUCTION

Background

The Society for Computer Applications in Radiology (SCAR) was formed several years ago to provide a forum for the exchange of scientific information concerning the use of computers in Radiology. SCAR was created under the auspices of the Radiology Information Systems Consortium (RISC), a non-profit organization dedicated to stimulating the development of quality computer systems in our field.

The Society, SCAR, serves individuals interested in computer applications and wishing involvement in an organization dedicated to these purposes. The Journal of Digital Imaging (JDI) is the official journal of SCAR. RISC has institutional members, not individual members, and typically arranges contracts with commercial vendors for joint development efforts with member institutions.

The American College of Radiology (ACR) sponsored eight Conferences on Computer Applications in Radiology every other year since the early 70's. Because of financial concerns, the ACR turned responsibility for the conferences over to RISC for the 9th Conference, held in Hilton Head in June 1988. The ACR co-sponsored that meeting. These conferences have played an important role in the revolution in the use of computers in Radiology, with dramatic improvements in the technology and applications seen at each meeting. The earliest meetings were dominated by prototypes of Radiology Information Systems (RIS) as well as early attempts at computer-assisted diagnosis. At the latest meetings, Picture Archiving and Communications Systems (PACS) and image processing, such as 3Dreconstructions, have dominated the presentations.

Computer Assisted Radiology (CAR) is the organization which has sponsored three very successful CAR symposiums in Berlin (held every other year). Heinz U. Lemke, Ph.D., has organized and masterly led those efforts from the very beginning. The CAR meetings have been oriented more toward the technical side, but offered two simultaneous tracks, one

technical and one more clinical. CAR has demonstrated the strength of both the European academic institutions and the commercial vendors in these fields. CAR has been a major player in organizing the European leadership and has also managed to attract many international colleagues as well.

What does all of this have to do with S/CAR '90? This symposium represents the merger of these two previously separate series of conferences. S/CAR '90 is the 10th Conference on Computer Applications in Radiology and the 4th Conference on Computer Assisted Radiology. We believe that we have combined the best of both approaches in this conference, with dual tracks, tutorials, workshops, tours and this hardbound book. By bringing the **technical and clinical strengths together** and converting these meetings into truly international events, the quality, impact and appeal have been raised substantially. This symposium attracted 32 commercial exhibitors, more than any other meeting of its kind.

S/CAR '90 Program

The program for S/CAR '90 and the contents of this text are divided into the following major categories: Management Information Systems, Picture Archiving and Communication Systems, Image Processing, and Teaching and Research. Each of these areas will be described below.

Management Information Systems

During the earliest ACR Conferences as described above, the first prototype RIS's were under development at several leading academic institutions. No viable commercial products existed. Over the years, successful implementations have been presented and the commercial development of good management systems blossomed.

The presentations concerning management systems in these proceedings deal mostly with reporting systems and the application of artificial Intelligence (AI) techniques. Speech recognition systems have improved dramatically in the recent past and several papers demonstrate the current applicability in our field. The use of rule-based programming and so-called expert systems are presented in a series of papers, including managing the display of digital images and assisting diagnostic decisions.

Teleradiology, the transmission of images between two distant locations, could be considered part of PACS. These systems offer the opportunity to provide superior service to our referring colleagues at a time when such service is competitively most important. Advances in automated scheduling and integration with other systems in the hospital are also important topics today.

Picture Archiving and Communications Systems

PACS are expected to replace film for the acquisition, transmission, storage and display of medical images in the future. Although there has been much enthusiasm on the part of both academic and commercial developers, few systems are clinically in operation at this time. RIS development took a decade to reach the level of hundreds of installations. PACS may follow a similar pattern, unless they can be found to be cost-effective soon.

Several institutions have developed prototype systems and a few have clinical trials in place. These experiences are presented in several papers and show considerable progress, even since the November meeting of the Radiological Society of North America (RSNA). Exciting new developments in the United States, Europe and Japan are presented, taking advantage of the latest improvements in technology.

The coexistence of film and PACS has become more of a reality as experience in PACS grows. These hybrid transition approaches are well documented in several papers. The importance of standards, including the ACR-NEMA standard, is also presented. The critical nature of the design of the digital workstation is brought into focus in papers dealing with the workstation as well as in papers on clinical design and evaluation.

Image Processing

The term image processing is quite general, incorporating a variety of different mathematical and computational tasks. Although image processing techniques have been used for years, only recently have some of these ideas appeared to have real clinical significance. Three-dimensional (3D) presentation of computerized tomography (CT) is still being refined, but much more attention is now being given to magnetic resonance imaging

(MRI). As demonstrated in several papers, cardiac MRI applications demand 3D and time-motion presentations in order to be fully understood.

Surgical planning continues to benefit from a variety of image processing techniques. In addition to facial reconstruction, the implantation of orthopedic prostheses is facilitated significantly. In addition, image processing is beginning to show promise in other areas such as cholangiography, chest examinations and mammography.

Teaching and Research

Computer-assisted instruction (CAI) has been applied in Radiology for years, but has not yet realized widespread acceptance. The difficulties in course preparation, the cost of equipment and the limited experience on the part of radiologists have all contributed to the lack of success to date. As can be seen in the papers involving computers in teaching, the combination of new software, cheaper and more powerful personal computers, and much more familiarity among radiologists is rapidly changing the way we teach our specialty. Although still important in education, the videodisc appears to be giving way to digital imaging techniques for medical images.

AI and speech recognition also find their way into the teaching and research area, and the combination of PACS with personal workstations for teaching as well as clinical case presentation makes great sense.

In the research section, MRI, ultrasound and mammography share the attention, with a potpourri of promising applications. Some of these developments require supercomputers while others are managed on the desktop.

Ronald L. Arenson, M.D.

Professor of Radiology

*University of Pennsylvania School of Medicine
Philadelphia, PA*

Future Symposia

The following meetings are already well along in the planning stages. The CAR meetings will be held out of the U.S. every other year to alternate with the S/CAR meetings to be held in the U.S. Please mark your calendars for the following:

Computer Assisted Radiology, CAR '91, July 3-6, 1991,
Berlin, West Germany

Symposium for Computer Assisted Radiology, S/CAR '92,
June, 1992, U.S. site to be determined

Computer Assisted Radiology, CAR '93, June 30-July 3, 1993,
Berlin, West Germany

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Information Management Systems

General Session

Film Labels: A New Look

Tim B. Hunter and Robert Morrison

Department of Radiology, University of Arizona Health Sciences Center,
Tucson, AZ

Every diagnostic image should be properly labelled with pertinent patient information, such as the patient's name, hospital number, date of birth, and exam date. This is usually no problem with CT, ultrasound, Nuclear Medicine, and digital radiology studies because the imaging equipment is designed to automatically put the patient information in appropriate places on the films, typically across the top of each image or on a film header. However, most diagnostic radiology still involves the use of everyday x-ray films. These films usually are labelled by some type of film flashcard system.

No matter the method used, the majority of the labels always seem to be upside down or backwards when the film is put up for interpretation. A program, LABEL, was written to create a new font set containing upside down, tilted, and mirror image characters for a Digital Equipment Corporation (DEC) LA/75 dot matrix printer and an Okidata Microline 192 dot matrix printer. A film label was then designed to use this new font set to create film flashcard labels so they are immediately readable, no matter how the film is put up. The program was written in compiled BASIC for stand-alone systems and in MUMPS to be integrated into the IMAGES radiology image management system used at the University Medical Center in Tucson, Arizona. LABEL captures patient data from the IMAGES information system, and writes out an appropriate film flashcard using the DEC

printer.

LABEL also calculates the patient's age from his or her date of birth information. The age is then printed on the flashcard. It is much easier to read the patient's age off the film label than to calculate it mentally from the patient's birth date. In the case of infants under a year of age the program calculates their age in months, weeks, or days. This has proven to be particularly helpful with neonates only a few days old.

It is recommended that similar systems be instituted in other hospitals. This could take many forms. A special program could be written for one's own hospital information system so that it prints flashcard with special upside down and mirror image fonts. Or one could use the compiled BASIC form of the authors' program to control a dedicated microcomputer/printer setup to produce flashcards (write to the

authors for details concerning program availability). Any program to print custom designed film flashcards should be easy to use and allow ready modification of the label through simple menu choices. Thus, the power of the computer not only allows you to have special fonts for high visibility of critical information, but it also allows you to change the label at will. You might want to move around information into different positions, delete certain information, bold information, italicize it, or underline it. All of this is possible with computer control of the film label.

Of course, the important message here is not so much that of a computer program to design film labels but that film labels should be accurate, legible, and easy to read. The film label is a most important item and should not be neglected. The use of special fonts makes it less necessary to

take a film down and turn it around to read the label. Good film labelling will not necessarily lead to good radiology, but bad film labelling with inattention to detail will inevitably lead to bad radiology.

Intelligent Automated Appointment Scheduling: Advantages for a Large Radiology Department

Steven M. Montner, Paul D. Davis and Richard E. Sayre

Department of Radiology, University of Chicago Hospitals and Clinics,
Chicago, IL

In our large hospital-based radiology practice, difficulty in scheduling patient appointments is a highly visible problem. A written schedule for each subspecialty or examination suite may be accessed by only one appointment coordinator at a time. Our solution has been to provide a Radiology Information System (RIS)-based online scheduling capability, accessible from any location for any examination offered. Eliminating the need for a written ledger, it allows multiple users to simultaneously access centralized schedules. Retrieval of patient folders containing prior comparison examinations is automatic, and could be extended to a PACS to initiate pre-assembly of prior images in a workstation from an image archive. The schedule for any given day may be reviewed, allowing the radiologist to anticipate an examination that may require specific attention or imaging protocol.

Our scheduling module is integrated into the RIS developed at the University of Chicago, patterned after the Missouri Automated Radiology System (MARS). Given a statement of examinations requested, the module suggests the best available time and examination suite. Information is derived from logical templates defined for each examination and examination room. The user sees a graphic display of targeted rooms and times, and automatic scheduling is supplemented by a group of override capabilities. Templates accommodate differences between subspecialty practices, weekly schedules, weekends and holidays, and can be easily modified to adjust to changes in staffing or departmental policy. For example, a 1-hour 'slot' routinely reserved each morning for adult outpatient CT-guided biopsy procedures may automatically be released for general use if a biopsy has not been scheduled within 24 hours of the time in question. The module avoids scheduling conflicting times for a given patient, and a further modification will

avoid conflicts from improper examination sequencing relative to contrast material retention or iodine usage.

Patient throughput is enhanced because patients are preregistered at the time of scheduling. If additional demographic or billing information is needed, it may be obtained prior to the patient's arrival in the Radiology Department and the patient may proceed more quickly to the examination room. Since the implementation of the computerized scheduling module in GI and CT, a greater efficiency of room utilization has increased the number of patients examined. The ease of scheduling an appointment has increased, probably because several appointment coordinators are able to access the centralized schedule simultaneously. Without increasing appointment coordinator staffing, the hours during which calls for scheduling appointments may be taken has been greatly extended. Any day's schedule may be viewed from any Radiology Information System terminal, including home PC's via a modem, to enable radiologists to more efficiently plan their day. Scheduled invasive procedures are continuously displayed at several locations throughout the department, updated every five minutes

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Expert System for Radiology Group Physician Scheduling

David Avrin

Sacramento Radiology Medical Group, Carmichael, CA

Suzanne Lehmkuhl

Computer Science Department, University of California at Davis,
Davis, CA

INTRODUCTION

Balancing the preferences and needs of the individual radiologists with the requirements of a group practice can be an unmanageable and potentially unsolvable problem. With the median size of private group practices in the United States at almost ten radiologists, the time required for performing this scheduling task manually appears to increase geometrically with the number of radiologists. It is hard to justify the costs associated with a radiologist diverted from other tasks or use of time to perform this one, with the availability of the program described in this paper.

Over the past ten years, we have developed a rules-based expert system, CALENDOC, that can be customized to a particular practice. From the specific requests of the radiologists for time-off preferences, conflict-free multiple call rotation schedules and a prioritized daily work schedule are generated.

Initializing the program for a specific practice can take a few hours. Entering the time-period specific information through the screen driven data editor is a much shorter process. Modifying the data is trivial. CALENDOC can then take that information and generate a complete schedule for up to twenty radiologists for an entire year in about one minute, depending upon the micro-processor type and speed in any IBM/MSDOS compatible system.

BACKGROUND

Radiologist scheduling is perfect for attack by a constraint or rules-based expert system. This scheduling task is usually performed manually, sometimes with some computer aided word-processing or spreadsheet format. But the rules, "the whys and the whens," are all done in someone's head, usually of one of the radiologists. For any given practice, the rules are usually very complicated. But in fact, there are more similarities than differences from practice to practice, and even from radiology to other specialties.

We started in 1980 with a program built specifically for our practice. No commercially available programs existed at that time. In 1986 a program was reported from the Mallinckrodt Institute of Radiology.(1) Also, we have evaluated a product developed for anesthesia groups.(2) Two years ago, modifications were made to generalize the program to potentially any similar practice.

One of the instigating factors in initiating this project was the popularization of the Pascal programming language. It had a feature that rendered it perfect for this task: the only widely used language that had provisions for scalar variables and set theory operations on those variables. Concepts like the whole set of radiologists, the set qualified to take first call or neuro call, the set of radiologists on vacation this week or next week, the set available to work this week, etc. form the core of the logic of our algorithm.

PLEASE ENTER THE NUMBER OF DOCTORS (5-20): 18

PLEASE ENTER THE NUMBER OF LOCATIONS (4-15): 13

ENTER THE LINEUP OF DOCTORS USING THREE LETTER CODES:

ANG AVR BRO FEL FER HLZ JMS LI MOO MUK MWD NYB PAR PET SWD WHI ZIB LOC

Press <esc> to continue

Figure 1. Query and input screen for basic group information.

ALGORITHM DESCRIPTION

There are two parts of the scheduling problem. The first is the determination of major call - that is call taken a week or weekend at a time. The second is the determination of who works where on any given day. These are very separate and almost unrelated problems.

Major Call:

Four pieces of input data determine the solution for major call:

1. which radiologists are eligible to take a specific call rotation - Figure (2)
2. the vacation/week off requests* - Figure (3)
3. special requests for weekends off
4. assigned weekend call for holidays or other purposes.

(*These are determined by a manual process external to the program in keeping with the practice rules, not to exceed a maximum number that would leave jobslots uncovered.)

ENTER THE LINEUP OF THOSE AVAILABLE FOR FIRST CALL. THOSE DOCTORS PLACED AT THE BEGINNING OF THE LINEUP WILL RECEIVE MORE ASSIGNMENTS.

2 DOCTORS WILL RECEIVE 3 CALL WEEKENDS AND 4 DOCTORS WILL RECEIVE 4 CALL WEEKENDS.

USE THE THREE LETTER CODES:

PAR LI MUK MOO FER SWD

Press <esc> to continue

Figure 2. Weekend call roster information screen.

ENTER THE VACATION SCHEDULE OF THE PRACTICE BY WEEKS. ALLOW NO MORE THAN FOUR DOCTORS OFF PER WEEK AND USE THE THREE LETTER CODES TO DENOTE THE DOCTORS:

```
WEEK 1: FER ZIB
WEEK 2: FEL
WEEK 3: MOO AVR ANG
WEEK 4: HLZ MWD SWD
WEEK 5: ANG NYB
WEEK 6: FER ZIB
WEEK 7: HLZ MUK WHI
WEEK 8: JMS NYB FEL
WEEK 9: AVR JMS LI
WEEK 10: MWD SWD PAR
WEEK 11:
WEEK 12: HLZ NYB WHI
WEEK 13: BRO LI JMS
```

Press <esc> to continue

Figure 3. Vacation selection screen.

From these data, a major call schedule can be determined, for multiple call rotations. The algorithm that we have been using for a number of years works well. The goal of this algorithm is to maximize the spacing between on-call weeks or weekends for the greatest number of participants, and to absolutely obey certain prohibitions which include:

1. on-call the weekend after a week of time off
2. on-call the weekend beginning a week of time off
3. on-call a requested weekend off
4. on-call two weeks in a row
5. on two different call rotations at once.

The algorithm works as follows: The assigned calls are inserted into the schedule array, as are the requested weekends off. The vacation requests are inserted. The remaining call slots are then filled in rotation by those eligible without regard to the constraints (2) and (3) above.

Then a group of procedures sweeps through each call schedule radiologist by radiologist, week by week, and checks for "eligibility" for that particular weekend, and if a violation is found, starts searching the nearest weeks, and if necessary the entire schedule, forward and backward, for a permissible "swap". If such a swap to another week with another radiologist is found, then it is made. Assigned weekends are not swappable. Each entire specific call schedule is massaged this way, first with at least four week spacing between call intervals, then three week if no solution can be found, and then two week, i.e. every other week intervals. An error is generated if no "clean" (no violations of constraint) solution can be found.

Weeknight Call Rotations (Minor Call):

One night at a time weeknight call rotations are implemented, and are dependent primarily on not being on a week off, and not on day off either the day of call or the day after.

DAILY WORK ASSIGNMENTS

Daily work assignments are made with a scheme best described as two-dimensional prioritization. The two basic concepts are that certain daily assignments are more important or sensitive to the practice in their staffing and can be ranked; and that for each daily work slot there is a prioritization of who works there. In fact, in this era of subspecialization even in private practices, certain radiologists may not be eligible for particular slots. See Figure (4).

Note that the ranking is from the perspective of the needs of the practice, not the preferences of the radiologist. Individual preferences are accommodated indirectly by not including radiologists in rosters for locations that they do not want to work, and by a higher priority ranking in those locations that they desire, if congruent with the desires of the group.

ENTER THE PRIORITY ROSTERS FOR THE WORK SITES
AS WELL AS ANY ROTATION VALUE FOR THE ROSTERS IN THE
FORM Qn WHERE n VARIES FROM 0-13 AND Q0 IMPLIES NO
ROTATION. UTILIZE THE THREE LETTER CODES FOR
THE LOCATIONS AS WELL AS THE DOCTORS.

WEEK 01: (FOR WEEK 1 PLEASE ESTABLISH ALL WORK LOCATIONS)

LOCATION: SJP ROTATION: Q 2
HLZ SWD FER LI
LOCATION: IC1 ROTATION: Q 0
WHI HLZ MUK FER ZIB JMS
LOCATION: IC2 ROTATION: Q 0
HLZ MUK FER JMS ZIB ANG
LOCATION: MO1 ROTATION: Q 0
MWD FER MUK JMS ZIB
LOCATION: MO2 ROTATION: Q 0
FER AVR JMS MUK LI ANG ZIB

Press <esc> to continue

Figure 4. Daily work slot priority roster first screen.

One other task that is performed before actually assigning the daily work slots is to distribute additional days off in some equitable or proportional manner. These additional free days arise from less than a maximum permissible number of radiologists being on vacation or meeting weeks. Our practice allows up to three radiologists off each week, but some weeks are chosen by only one or two radiologists, or not chosen by anyone. CALENDOC allows and encourages that kind of flexibility.

One minor point is that Mondays and Fridays off, which generate three day weekends (a valuable commodity) are kept track of separately from midweek days. Also, any specially requested days off are charged to the appropriate radiologist against his/her allocated number. CALENDOC also has provisions for occasional administrative days off, which are not charged to an individual's allocation of days off, but which do remove a radiologist from the set available for the daily work slots.

Finally, two additional flexibilities are provided. A radiologist can be allocated extra individual days off by trading for a full week off. A half-day off rotation also can be enabled and equalized.

At this point we should be left with just enough radiologists to do the day's work. The jobs are filled in the order of priority described above, as defined in the datafile. Each job is filled from the job slot roster, defined by query and input in the datafile, by the first available radiologist in that roster (not on vacation or day off, and not yet pulled for a higher priority slot). The rosters must have deep enough "bench strength", particularly for the lower priority positions, to make sure that all slots get filled. Too many dayoff requests, or inability to fill a job from the rosters generate error messages.

Two last features are that a roster (for example for MR) can be made to rotate on a daily, weekly or any multiple of weeks basis so that the number one radiologist goes to the bottom, and all others move up one position; that any or all rosters can be modified beginning any week, and repetitively throughout the schedule.

SCHEDULE OUTPUT

The actual schedule is stored in an array defined by date, call and location. However the work schedule printout can be by location, or turned around by radiologist, as shown in Figure 5. The radiologists usually prefer the second mode, while the technical and management staff prefer the first.

Output includes a tally screen that summarizes type and

number of call assignments, as well as days off, for each radiologist.

SUMMARY

We have describe a rules or constraint based expert system that is generic to the radiologist scheduling problem, yet can be customized for a particular practice. CALENDOC contains user-friendly query screens, and implements the set theory and other logic described above. It checks constraints without error that no human could reasonably be expected to perform.

Future developments include improved tree-structured query screens, and an "editing" version to allow for expected or unexpected changes.

CALENDOC allows practices and radiologists to schedule flexibly, reconciling individual needs with the requirements of the practice, while guaranteeing full coverage. It is a powerful time-saver for medium to large groups.

WEEK	7	CALL:			ASSIGNMENTS:									
		GEN	MRN	INT	ANG	AVR	BRO	FEL	FER	HLZ	JMS	LI	MOO	M
SAT	2/10	SWD	MWD	AVR										
SUN	2/11	SWD	MWD	AVR										
MON	2/12	ANG	MWD	AVR	MS1	MO2	MG1	MS2	IC1	VC1	IC2	SJP	DO2	V
TUE	2/13	FER	MWD	AVR	MS1	MO2	MG1	MS2	IC1	VC1	IC2	DO2	MF	V
WED	2/14	PAR	MWD	AVR	MS1	MO2	MG1	MS2	IC1	VC1	IC2	B/O	MF	V
THU	2/15	LI	MWD	AVR	DO2	MO2	MG1	MS2	IC1	VC1	IC2	SJP	MF	V
FRI	2/16	FER	MWD	ANG	MS1	MO2	MG1	MS2	IC1	VC1	IC2	SJP	MF	V
ASSIGNMENT:		GEN	MRN	INT	DO1	DO2	SJP	IC1	IC2	MO1	MO2	MMD	MRI	
MON	2/12	ANG	MWD	AVR	SWD	MOO	LI	FER	JMS	MWD	AVR	PET	NYB	
TUE	2/13	FER	MWD	AVR	ZIB	LI	SWD	FER	JMS	MWD	AVR	PET	NYB	
WED	2/14	PAR	MWD	AVR	MWD	***	SWD	FER	JMS	ZIB	AVR	PET	NYB	
THU	2/15	LI	MWD	AVR	PET	ANG	LI	FER	JMS	MWD	AVR	SWD	NYB	
FRI	2/16	FER	MWD	ANG	PET	PAR	LI	FER	JMS	MWD	AVR	SWD	NYB	

Figure 5. Printed output by radiologist and location

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1. AJR 147:203-204, July, 1986
 2. Your Software Company, Norcross, Georgia
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TurboPlus is a trademark of Nostradamus Software.
MSDOS is a trademark of Microsoft Corp.

HIS/RIS Integration: Experiences & Future Developments

Maarten L. Koens, Rudolf J. Weber and Albert R. Bakker

BAZIS Central Development & Support Group Hospital Information Systems,
Leiden, THE NETHERLANDS

Summary

Radiology Information Systems (RIS) are usually developed as stand-alone departmental systems to serve the basic information needs of the radiology department. Coupling with the Hospital Information System (HIS) operational in the surrounding hospital is usually restricted to patient identification from the hospital's patient database and recording of examinations performed for billing purposes. However further integration of these systems is needed to improve the communication between the radiology department and the in- and out-patient departments in the hospital.

1. Introduction

Radiology departments are part of the surrounding hospital and have many lines of communication to and from the various in- and out-patient departments. In spite of this Radiology Information Systems (RIS) usually have only a meagre coupling with the Hospital Information System (HIS) operational in the hospital. The import of patient identification data from the HIS to the RIS and the export of data on procedures performed for billing purposes are quite common. In few cases order entry from the in- and out-patient departments is possible[1]. There are also some examples of report-printing in the in- and out-patient departments.

In which way can a further HIS/RIS integration improve the communication between the radiology department and other hospital departments and even to requesting physicians outside the hospital? In which way can this improved communication contribute to a better performance of the hospital as a whole? We will try to answer these questions by sharing our experiences in this field. We base our experiences on the BAZIS HIS. This HIS is built from about 70 subsystems around a central hospital database[2]. The

BAZIS RIS, called RADI, is one of these subsystems, with functions for patient registration, examination scheduling, archive management, film-folder tracking, report generation and patient tracking. The BAZIS HIS is running in 40 Dutch hospitals, including 7 University hospitals, which have together about 20,000 acute beds. The BAZIS RIS is running in twenty hospitals. In the next sections we will give our experiences with HIS/RIS integration in the Leiden University Hospital(LUH) in relation to the improvement of the communication, planning and management of the flow of patients, reports and X-ray film-folders[3,4]. We also try to indicate the direction of future developments in this field.

2. HIS/RIS integration in appointment scheduling

Communications with other departments and the planning of examinations can be improved in two ways:

- to give the radiology department and in- and out-patient departments insight into each others appointments while making a new appointment for the same patient
- to decentralize the appointment scheduling to the requesting physician or department.

2.1 Scheduling supported by other scheduling data

In the LUH both the radiology and out-patient departments make use of appointment scheduling functions and take information about other scheduled visits of the patient into account. Insight into each others appointments is found to be an advantage because it gives the user and the patient the opportunity:

- to prevent the exposure of the patient to more than one heavy examination in one day
- to combine the various appointments of a patient to avoid waste of time
- to schedule the X-ray appointment a predefined period (e.g. 24 hours) in advance of an out-patient visit in order to guarantee the availability of the report before patient's visit to the out-patient department.

2.2 Decentralized order entry

As an experiment we authorized a small group of users of one of the internal medicine wards to make use of the radiology appointment scheduling functions for a limited set of examinations. This experiment was done to find out the user requirements for this decentralized function which are expected to differ from those of the radiology

personnel. Some of our experiences were[5]:

- The possibility to choose an appointment date and time that best suits the patient is found to be an advantage.
- Date and time of the appointment are registered immediately. Therefore coinciding appointments occur less frequently.
- For some examinations the waiting time for an appointment is too long. In this case the radiology department is called by phone to schedule the patient in the overflow area of the agenda.
- 45% of the requests for an examination is scheduled by the users in the ward. The remaining examinations require consultation with the radiologist or chief technician.
- The radiology department experiences a decrease in contacts by telephone.
- For the radiology department it sometimes is more difficult to realize a balanced workload.

Future developments will be stimulated by the realisation of the BAZIS nursing information system. In this system a request for an appointment for e.g. a colon X-ray

'explodes' into a series of actions and registrations[5]:

- check on possible contra-indications and conflicts with other appointments for this patient
- check on desired date and time in the agendas of the radiology department and registration of the appointment
- identification of all nursing activities related to a colon X-ray and registration of these activities in the nursing workplan
- registration of medication orders and initiation of transport of the patient to the radiology department.

3. HIS/RIS integration in reporting

As soon as the report is authorized it should be available for and sent to the requesting physician. There are four ways in which this could be supported by the integration of RIS and HIS:

- The authorized report is sent immediately via the HIS terminal network to a printing device in the ward or out-patient department.
- The authorized report is sent immediately to the information system of the requesting physician in- or out-side the hospital.
- The requesting physician can ask the system for all the available reports with a selection on a certain period

or on certain examinations.

- The existence of an authorized X-ray report can be reported to the in- and out-patient information system that keeps track of the progress of all patient's examinations, lab tests, etc. The requesting physician can, at the moment of his own choice, ask the system for all the available results.

In the LUH reports are printed in the in- and out-patient departments immediately after authorization of the report. The printing of authorized reports in the typing area of the radiology department is almost redundant:

- All the reports are on-line available for a period of more than 5 years.
- Users throughout the hospital have access to the on-line medical record system, called PATIENT, to retrieve information about lab results, including pathology, radiology examinations and reports, admission and discharge diagnosis, surgery information, radiotherapy treatments, blood transfusions and medication prescriptions. PATIENT is used by users throughout the hospital, including radiologists to support their diagnostic process.
- The development of a system called MIRAGE[6] that supports the transport of ADT data, radiology reports and lab results via a public data network to the information system of the patient's general practitioner(GP). This system is in use since April 1989 by 5 hospitals to support the communications with 18 GP's.

We make use of a so-called EDI service (Electronic Data Interchange) to exchange data between the HIS and the GP information systems by means of agreed standard messages. These standards are based on the EDIFACT[7] standards used in the logistics environment for trade data exchange. We defined messages for ADT data, radiology reports and lab results. New messages will be defined for specialist letters, results of microbiology-tests and pathology. In 1990 we plan to extend the implementation of this system to 13 hospitals and more than 70 GP's.

The total number of exchanged messages in 1989 was 12,500. This number will increase in 1990 to more than 50,000 messages. At this stage of the MIRAGE project the following conclusions can be made:

- . The network is reliable and the use of the EDIFACT

- standard offers no technical problems
- . The gain of time of about 30 hours is not yet considered to be relevant by the participating GP's
- . GP's consider the integration of the communication into their information system to be the most important benefit.

In the long run the reporting of X-ray examinations will become part of an out-patient information system with which the requesting user can keep control of the progress of lab tests and exams, and has access to the available results and reports.

4. HIS/RIS integration and archive management

The availability of old and new X-ray film folders is essential for:

- the radiologist while reporting new images
- the specialist preparing patient's out-patient visit
- the specialist preceding and during the admission of a patient.

In order to realize both a better planning of archive personnel workload and high service levels to the requesting specialists, requests for film folders have to be registered at the moment an appointment for X-ray examinations or an out-patient visit or the admission is scheduled. With this information the archive management system can generate information about which folders have to be transferred when to which departments.

Before the introduction of the system departments used to send requests to the different file rooms in the hospital. In daily practice this is found to be an unstructured and unreliable way of communication:

- requests arrive written on a variety of notes and forms, or orally either by telephone or in person
- requests are sent to the wrong file room
- requests are sent for patients that never visited one of the X-ray departments before
- requests arrive too late.

Integration of the request film folder function of the RIS in the HIS can yield a major improvement of the communication between the requesting departments and the file rooms, and an improved operation of the file rooms.

In the LUH most of the in- and out-patient departments request film-folders via their HIS display terminals. For each archive location the archive management system

collects all the requests that have to be dealt with within a certain period. Only requests for film folders that are really available in the archive location are presented on a pull list in archive order. Requests for lendable folders can be printed on a list at the borrowers location. The number of requests increased with the implementation of the decentralized request function. The users were interviewed[4] and were found to have positive experiences with the system:

- The overview of all the available film folders with the possibility to point out the wanted folders encouraged the user to issue a request.
- The required time for requesting has been reduced considerably.
- On the other hand users became aware that they sometimes submitted a request for folders that should be already in their possession!
- The users experienced the archive to be a reliable and fast supplier of the requested folders: the lead time was reduced considerably. This improved the relations between borrowers and archive staff.
- The ratio of honoured/requested folders increased from 80 to 98% due to the more accurate registration of the actual location of the folders.

The archive personnel experienced:

- a fast decrease in request forms, telephone calls and urgent requests
- a more structured method of working and a more balanced workload
- no request for folders not present in the file room occurred
- less time-consumption in searching for lost folders
- a considerable reduction of the number of lost folders

Although the number of requests increased with about 10% to 1000 requests per day and the number of examinations increased with about 18% from 1982 until 1988, the permanent archive staff in the LUH remained constant at 7.5 fte and the number of temporary staff was reduced from 0.2 to zero.

5. Conclusion

Integration of a RIS in a HIS environment provides a splendid opportunity to contribute to the optimizing of the patient care process in the hospital as a whole instead of the radiology department only.

Decentralized functions for scheduling of X-ray

examinations, requests for film folders and insight into authorized reports:

- improve the communication with the radiology department
- improve the planning of the workload in the radiology department
- realize higher service levels towards the in- and out-patient departments and to GP's
- realize a better service to the patient.

The direct availability of other patient related HIS data is a help in the diagnostic process of the radiologist. A major part of the workload(10-40%) in the radiology departments of Dutch hospitals is triggered by general practitioners. This emphasizes the need for further integration of the HIS with the outside world, especially with GP's-information systems.

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Management Systems

Low Cost Computerized Radiology Management Database System

C. Man, A. Olson, P. Masotto, et al

Department of Radiology, SUNY Health Science Center,
Brooklyn, NY

Introduction

A Computerized Radiology Management database System (CRMS) for Radiology has been in operation at the State University Hospital, Health Science Center in Brooklyn (HSCB) since November of 1987. The initial database system was a single user system. It is currently running under a local area network with nineteen workstations and will continue to grow with additional functions.

Our Radiology department performs 52,000 examinations annually including conventional X-Rays, nuclear medicine procedures, sonographies, CT, MRI and angiographic studies. The purpose of the CRMS was to enhance patient registration, to reduce patient registration errors, to automate patient ID flash cards, to facilitate archival operations, track film usage, generate statistic reports on a daily basis while compiling monthly and annual reports, to reduce lost films and to become a less labor intensive environment.

Hardware Architecture

The hardware of CRMS includes a file server, eleven Santa Clara diskless workstations, eight XT/AT workstations, a 1200 watts Uninterrupted Power Supply system (UPS) by American Power Conversion inc., a 60 megabyte cassette tape backup system from Emerald Inc., two network printers and local printers for

each workstation. The file server is an AT-compatible computer with an Intel 80286 processor of 8 MHz clock speed and zero wait state. This file server consists of 2 megabyte memory, one 360k byte floppy disk drive and two 150 megabyte hard disks mirrored. The file server also includes an 8-bit ARCNET network interface card (NIC) from Standard Microsystem Inc and two 16 bit Ethernet-type NIC, the Etherlink from 3Com Inc. The Etherlink uses the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) access scheme with a 10 MHz baseband transmission. The ARCNET uses token-passing access scheme with a 2.5 MHz baseband transmission. The Santa Clara workstations are diskless XT computer with a 640k byte RAM memory, a built-in Ethernet NIC with a boot ROM. Each XT/AT computers are IBM compatible with 640k byte RAM, a 360k byte floppy drive, a 20 megabyte hard disk and an 8-bit ARCNET NIC manufactured by Standard Microsystem Inc also. All the diskless workstations are connected into two different linear bus systems to the file server with its two Etherlink NIC via RG-58 coaxial cable. Using the two separate linear bus topologies ensures continuous patient registrations even if one of the Ethernet NICs in the file server malfunctions. All eight XT/ATs are connected to an active hub using star topology as shown in Figure 1. The ARCNET NIC of file server is connected to the active hub. We decided to use the ARCNET for the XT/ATs is to allow comparison of speed, reliability, accessibility, ease of workstations addition between two networks. The UPS ensures the consistency of the commercial power and allows enough battery power to safely close all the files during a power outage. This UPS has the ability to monitor the commercial power line and shut down the file server safely when the commercial power sags below certain voltage or when there is a complete loss of the power. The installation of the UPS seems to have

alleviated previously experienced file corruptions among index files and data files. The first network printer is used to list each completed patient registration. The second network printer produces the patient's ID flash cards and the corresponding patient's index file card (this has been eliminated since the system has a proven reliability). The Emerald cassette tape system is used to backup the patient records daily. With its software package, system backup can be done automatically at midnight when the file server is most likely idle. Local printers are used to print patient registration forms and statistical reports at each workstation.

Software Architecture

The network software, (the Novell Advanced Netware 286 SFT version 2.1) was chosen after a careful investigation among other networking softwares (e.g. 3Com, IBM PC network software etc.). We feel Netware provides better memory cache, disk cache and a sophisticated system fault tolerance (SFT) with time transaction system (TTS). The memory caching and disk caching increase the speed of input/output of files from the file server. The SFT supports disk mirroring and disk duplexing. Utilizing these two techniques, data are written onto two disks simultaneously so that one disk provides a mirror image of the other. This function also provides an on-line disk backup system; therefore, if one disk fails, the backup disk will continue to operate without downtime or the loss of data. TTS employs a scheme called read-after write verification to guarantee data integrity. Once the data is written, the system reads the data to make sure that it is properly saved. The SFT and TTS provide the added on-line security of our CRMS.

The CRMS was written in Foxbase Multiuser Version 2.1. This database software package was chosen after benchmark studies on various database software including DBASE III Plus

with LanPack version 1.1, Paradox Version 2.0, and Clipper Version 2.1. The indexing speed and ease of programming in Foxbase Multiuser Version 2.1 appears to be more suitable for our database structure.

Database File Structure

The CRMS consists of four major files: patient demographic, patient examinations, monthly patient registration and statistics. The patient demographic file contains patient's full name, sex, social security number (SSN), date of birth (DOB), address, hospital identification number and radiology medical record number (MRN). In our institution, if the patient has a SSN, the last four digits of the SSN will be used as the MRN. However, if the patient is a foreigner or newborn, a MRN will be sequentially assigned to them by the registration clerk. This file is indexed in ascending order with the patient's last name, MRN and his/her DOB. The patient examination file contains the patient's last name, MRN, his/her DOB, examination date, and the related examination code. Each examination date will represent one record of data entry. The monthly patient files contain the patient's last name, MRN, his/her DOB, examination type, site location where the examination is initiated, examination date, shift (day or night), billing code, patient type, technologist who did the study and number of films used. In this file, each examination performed is regarded as a record. The patient type relates to the category of the patient that he/she belongs to; in-patient, employee, private, hospital clinic patient, and student. Various statistical files are generated from the monthly patient file based on examination procedure, diagnostic procedures, patient types, film usage and etc.

Program Layout

The CRMS is a menu driven system divided into different functions: patient registration, patient search, film input, to modify daily input, patient demographic lookup, report generation, and system utility. Each function is written as a program module so that additional functions can be easily added.

A. Patient registration:

After choosing patient registration from the main menu, the registration menu is displayed. The registration clerk must type the patient's full name and last four digits of the social security number as MRN. The system will determine if this patient had previous examinations in our institution by searching and displaying all the possible patients that will match this patient's last name and MRN. The registration clerk decides if there is an accurate match and selects the match. If a match is chosen, the computer enters the patient's demographic information. If no match is found, a complete demographic form will appear on the screen. The registration clerk is required to fill in all the demographic information about the patient. Next the clerk enters the examination type and the corresponding examination code. Here, multiple examination types and examination codes can be entered. These examination types and the examination codes are cross checked. Once the correct examination types and codes are entered, the registration is complete and a record of data entry, a registration form, index card and a flash card are printed by the respective printers.

Pre-registration can be done by simply changing the examination date. This module also allows any user at a workstation to check the list of patient registration according to examination type or patient name, or the entire list.

B. Film entry

Before the procedure is completed, each film is checked by a quality control

technologist. He/she enters the film usage for the study and the technologist initials performing the examination. The quality control technologist can list patients by name, by order of registration, or by examination type. Checking for the technologist initials or film usage on entry, the record is used to indicate the completion of examination.

C. Search

This program module allows a fileroom clerk to search for a patient and list out the examination history including the examination date and the types of examinations. The system can search the patient record based on name, MRN, SSN, and DOB or any combination of the listed information. Once a match is selected, the program lists the examination history of the match via a printer or on the monitor.

D. Report generation

This function can generate daily, monthly and annual reports. Reports are generated for each division (CT, MRI, US, Diagnostic, Special procedure, and Nuclear Medicine). Each report totals the number of examinations performed by the examination code based on the type of patient, it also totals each subcategory as shown in Figure 2. All of the statistical reports related to procedure, type of examination and patient type are further divided into regular and pediatric patients (patient under 18 year old).

A separate film usage report is generated based on film size and type.

E. Utilities

This function allows the database manager to backup monthly patient files to floppy diskettes, restore monthly patient files from floppy diskettes, update examination codes including examination fees, modify monthly files, modify patient demographic data and examination data files, and back-loading of all the previous examinations into examination file from the manual card file system.

Cost Analysis

The total costs of this system was less than \$60,000. The detail costs are shown below.

File Server includes 2 150 Megabyte	
hard disk & 2 Megabyte RAM	\$ 4,500
11 Diskless Workstation	\$ 9,900
8 AT Computer	\$ 16,000
Cassette Tape backup System	\$ 1,200
2 Etherlink NIC	\$ 1,000
9 ARCNET NIC	\$ 2,250
Active Hub	\$ 800
UPS	\$ 1,200
20 printers	\$ 10,000
Novell Netware SFT V2.1	\$ 3,000
Multiuser Foxbase V2.1	\$ 500
Cable and installation	\$ 3,000

Total	\$ 54,300

Conclusion

The previous registration system required the registration clerk to rummage through the patient card files to check if the patient had previous examination performed in our institution. If the patient card was found, the requested studies are typed on the card. A patient may have many cards under his name because of misfiling, misspelling and change of name (married). If the patient card was not found, a new card must be typed and filed. The registration form was typed next. When the technologist received the registration form, a flash card had to be handwritten before the examination could be done. Upon completion of the examination, the quality control technologist entered the completed study and film usage in a log book manually. The entire procedure took 7 - 9 minutes. The CRMS reduces this time down to 1 minute for the returning patient and 2 minutes for the new patient. The CRMS checks the validity of all the data entry, hence mistakes are minimized. Also, erroneous data are checked by the database manager and corrected. The

card files were centralized at the front desk, hence all patients were required to go to the front desk to register first before going to the respective division for the examination. With the CRMS, registration is done more efficiently by each division and the patient is not inconvenienced. Statistics on examination were done manually by counting from the log table in each division. This tedious report generation usually required the chief technologist in each division to spend days to get a monthly and annual reports and often the reports were not accurate. CRMS allows the database manager to generate each monthly report in less than 3 minutes and annual report in less than 10 minutes for the whole department.

Although Etherlink NIC uses a larger packet size (1024 byte) than ARCNET NIC (512 byte), this smaller packet size in ARCNET only affected the rate of transfer if data required to be sent is bigger than 512 byte. Also, the ARCNET transmits at a rate of 2.5 MHz as compared to Etherlink's transmit rate of 10 MHz. The ARCNET NIC is a much slower system, however, our system is not very busy and no appreciable difference between the two networks has been noticed. The I/O is not so busy that the transmission rate does not play an important factor in our configuration. One patient record is 490 bytes so the smaller packet size used in ARCNET NIC has no effect in our data transfer rate and ARCNET NIC is adequate for our CRMS. The major advantage of ARCNET NIC is the ease of adding more workstations and price. In order to add a new workstation for bus topology (Etherlink), one has to locate the end of the bus run and add the new workstation to the end. However, using star topology (ARCNET NIC), we can install an additional active hub to one of the ports of the previous active hub and eight more workstations can be added. This is major advantage for any system because the possibility to grow on any system is very

likely and is impossible to design a system to anticipate such growth before hand.

The system has been very well received by everyone in the department. Training is accomplished in a few hours. An increase in efficiency and accuracy is evident. Barcoding is being added to help in film tracking and special nuclear medicine features are being added presently. A billing module is available, however our institution utilizes a separate billing system so this module is not activated.

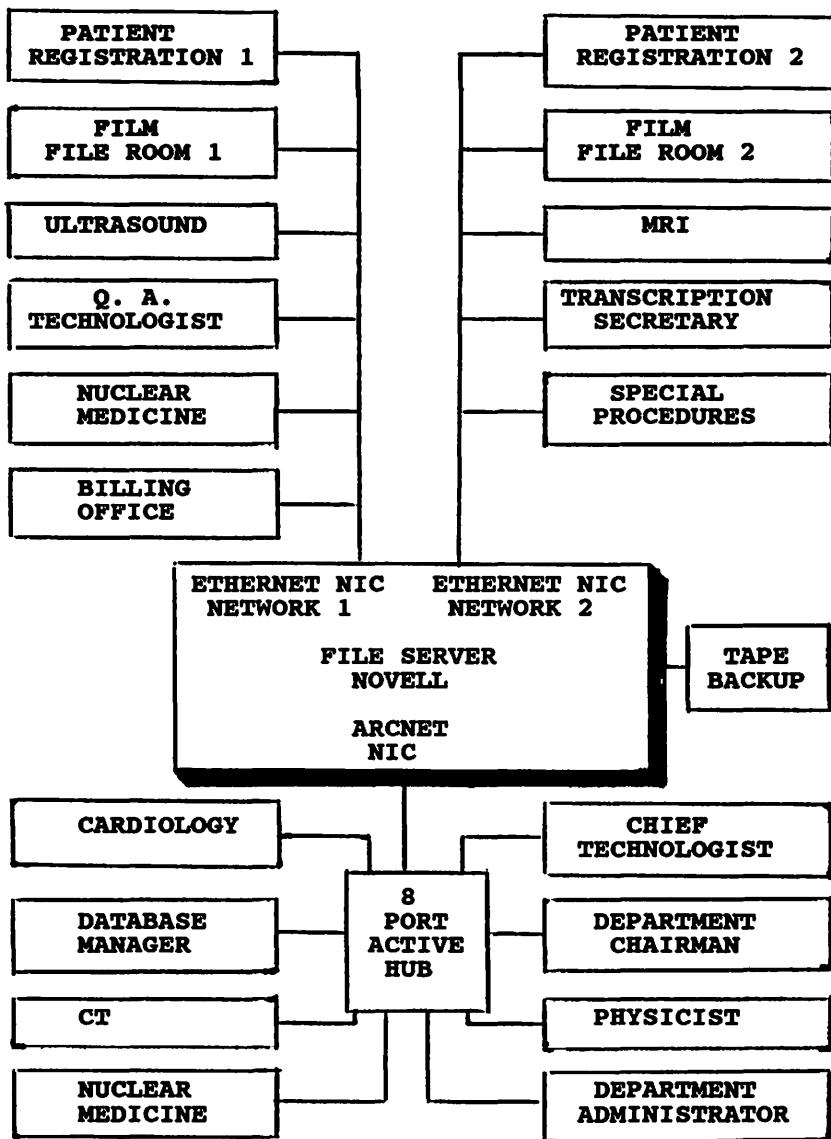


FIGURE 1 Hardware Architecture demonstrating two Ethernet networks and one Arcnet network

etc.						
Nuclear						
US						
MRI						
CT						
<u>EXAM</u>	<u>Description</u>	<u>INPT</u>	<u>OPD</u>	<u>Clinic</u>	<u>EMP</u>	<u>Total</u>
2004	CT Scan - Head	34	8	11	0	53
2204	CT Scan - Chest	9	4	3	0	16
2261	CT Scan - Body	31	27	7	0	65
2386	CT Scan - Neck	0	0	1	0	1
2387	CT Scan - Upper Ext.	1	0	0	0	1
2388	CT Scan - Lower Ext.	0	1	0	0	1
2389	CT Scan Abd-Stereo	3	8	0	0	11
2390	CT Needle Biopsy	1	1	0	0	2
Total						150

Figure 2: Sample Report

Experience With a Cost Justification Model for Evaluating Acquisition of a Radiology Information Management System

Jozef K. Cywinski and John A. Vanden Brink

Technology Marketing Group, Des Plaines, IL

Jack Hagan

IBM Medical Systems, Atlanta, GA

Summary

The Computerized Model developed jointly by TMG and IBM for cost analysis of planned installations of IBM Radiology Image/Information Management (RIM) systems was applied prior to the decision for the installation of RIM in three hospitals. The computed results for these hospitals indicate that the Model is a useful tool for the cost impact analysis necessary for justification of acquisition of a Spectrum* RIM. The projected cost savings resulting from RIM are such that the investment may pay back for itself in 2 to 4 years. It was also noted that the RIM cost savings constitute a substantial fraction (approximately 32%) of the total projected cost/benefit impact of a hypothetical installation of a complete PACS in these hospitals.

*Spectrum (partnership of IBM Corporation and Baxter Healthcare Corporation) RIM, formerly called IBM RIM

Introduction

The cost justification for acquisition of new technologies in health care is an important and often deciding issue.

This is particularly true of technology which purports to improve operational characteristics and thus reduce labor and material costs

but does not directly result in revenue generation. The emerging technology of PACS fits this definition and is dedicated to managing the staggering amount of information which is associated with a fully digital image and information support system. Data management archive and communication requirements for image generation and retrieval will likely exceed 10 gigabytes of information per day in the all digital department in a 400+ bed institution.

Costs for such complete systems range in estimates from several million dollars to ten to fifteen million dollars depending on the technology employed, radiology information system required, number of workstations and communication and archiving performance specifications. Obviously, an investment of this magnitude requires a thorough and detailed cost analysis of anticipated cost savings for present and projected operations and labor and capital equipment costs associated with the proposed technology.

Although we know of no retrospective studies of the cost/benefits of complete PACS installations, the studies for prospective application of PACS have been carried out by many investigators. Various models/scenarios for these were analyzed by Arenson of Penn University (1), Andriesen of Utrecht University (2), Dwyer of Kansas University (3), Huang of UCLA (4). They address mostly film use and management issues and the possible replacement of manual film handling by filmless electronic PACS.

TMG has developed a comprehensive Computer Model (5) to analyze in detail the day-to-day costs of both manual film handling and information handling processes (Phase I of the Model) as a basis of assessing current and projected costs using presently in

place processes. Such analyses have been performed in over 40 hospitals in the U.S. and Canada and the experience with the TMG Model was published (6). Subsequently, the outputs from the Phase I of the Model were compared against Phase II of the Model which represent radiology film/information management operations with PACS. This was done for UCLA and UMD Hospitals and the results were presented by TMG (7). From these experiences, we concluded that a substantial component of the total cost of manual image and information management represents "paper pushing" (appointments, scheduling, tracking and results, transcription) tasks in radiology. These tasks can be facilitated or replaced by a Spectrum RIM system and the time and cost savings from such replacement can be substantial. In this presentation we describe the application of computer modeling methodology, similar to that used previously (7) (8) by TMG for manual film management and electronic PACS cost analysis, to perform a cost impact analysis for planned installations of the spectrum RIM system.

Method

In order to specifically address the cost benefit issues of planned Spectrum RIM installations, our previously described (5), (6), (7) TMG computerized model for the cost analysis of image management in radiology was expanded. This was done in order to add procedural steps and their cost element which were specifically related to patient information and department management. The expansion of the model was done in cooperation with the working group at IBM Medical Systems specializing in medical/radiology applications. The additional elements to the Model and their respective cost/time contributions were presented to TMG by an IBM committee of 10 persons which encompassed members with experience in diagnostic radiology,

radiology administration, radiology nursing, radiology technology, radiology information management and medical systems software development and applications. Subsequently, the expanded Cost Analysis Model was programmed and tested in three medical centers and the feedback received from these centers was used to refine the Model. As a result of the cooperation and feedback from these hospitals, the refined Model was finalized and subsequently applied for cost impact analysis of proposed installations of Spectrum RIM systems.

Results

The manual vs. RIM costs were analyzed in the above mentioned hospitals in relation to the bed size and annual examination volume in respective radiology departments. The summary analyses of technical operating cost component for these hospitals are shown in Table 1 below.

Hospital Symbol	Bed Size	Annual Exams in Radiology	Annual Tech Cost with Manual Info Mgmt.	Annual Tech Cost with RIM	Difference %
1	630	148,000	1,892,000	1,781,000	5.9
2	577	83,000	1,668,000	1,430,000	14.2
3	334	59,000	814,000	672,000	17.4

Table 1: The comparison of annual technical operating costs for manual vs. Spectrum RIM information management method in the three tested hospitals.

The technical costs illustrated above represent actual hospital spending allocated to labor and materials for patient image handling and information management. If the RIM installation is to bring about anticipated savings, the methods and means of patient information management and the work flow in the department should be readjusted. This may require re-qualifying and/or reviewing some of the personnel positions. If and only when these changes are implemented, the RIM system can bring about anticipated effects. In addition to the above day-to-day potential savings and other benefit of RIM installation may be in the cost avoidance category. It is a general trend that the annual procedure volume in radiology increases from 3 to 15 percent.

Such increases are usually associated with additional costs of hiring new personnel and spending funds on materials and other costs. If the RIM installation can facilitate work flow and the time required for tasks associated with "paper pushing", the costs of hiring additional help to accommodate increased volume can be avoided altogether. The Table 2, below, illustrates the comparison of manual vs. RIM operation for 10 year projected cumulative labor costs.

Hospital Symbol	10 yr proj. labor (manual) (PV cumulative in \$1000's)		10 yr proj. labor (RIM) (PV cumulative in \$1000's)		Cumulative Cost Avoidance (PV in \$1000's)	
	Tech	Cler	Tech	Cler	Tech	Cler
1	9,510	4,155	6,906	2,386	2,604	1,769
2	4,267	3,986	3,222	1,925	1,045	2,061
3	2,969	1,941	2,234	924	735	1,017

Table 2: The comparison of cumulative labor costs 10 year projections for manual vs. spectrum RIM information management method in the three tested hospitals.

In discussion with the institutions who used the model for evaluation of the Spectrum RIM installation, they had the following comments regarding the model itself and the application of modelling to cost justification issues:

- The TMG model methodology is scientific and thorough. The model can be customized to each institution which is perceived as a requisite because of the differences between institutions.
- The data provided by the model is helpful as a base and indicator of cost justification issues in consideration of acquisition of a Spectrum RIM system and the concept of modelling is useful. However, modelling and cost justification are not adequate by themselves to justify the acquisition; there have to be other reasons, e.g., improved performance, quality of care, etc.

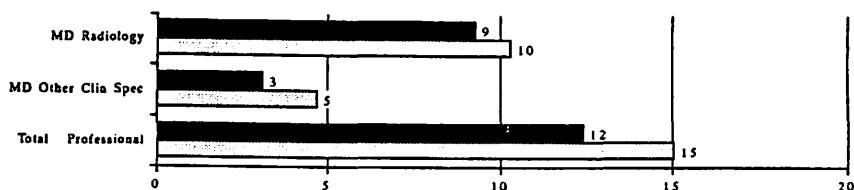
- The model identifies increments of time and costs that can hypothetically be saved by installation of the Spectrum RIM and the assumptions underlying the hypothesis can be changed for "what if" analyses. However, a question is whether all the aggregate savings will, in practice, add up to higher throughput or lower FTE's. The issue is, assuming the savings be made, whether the combination of savings will work out in a way that is operationally acceptable and whether the time saved can be put to good use.
- The modelling does help in identifying where savings can be made through operational improvements and acquisition of technology. It is a good complement to the acquisition process.
- It will be helpful when adequate data has been accumulated to compare actual experience to hypothetical savings.
- There is a fair amount of time involved in collecting the data but it's recognized as necessary to obtaining an accurate analyses. "You get out of it what you put into it," was the comment of one participant.
- The report is "a little overwhelming and busy when you first look at it but when you review it, all the information is there."

Summary

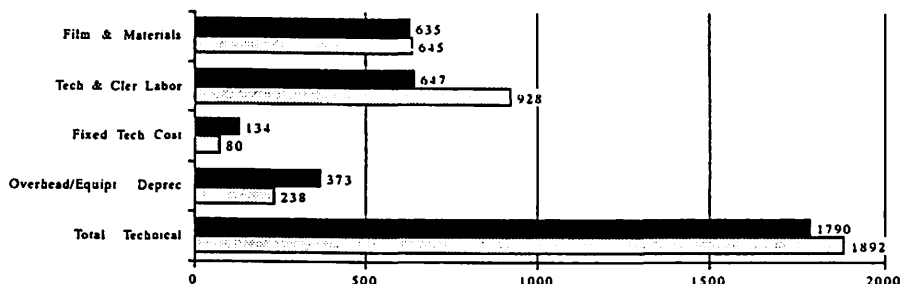
In summary, the hospital receives two management reports with a Executive Summary supported by a detailed spread sheet analyses of procedures, task times, consumables and amortized capital equipment expenditures.

Phase I portrays costs of current methods of information and management and highlights such areas as costs by modality and exam, professional and technical costs, comparison to national averages, with reference staffing and procedure volume, 10 year projected costs if no action is taken and an evaluation of the cost savings potential of reduced hospital stay.

Phase II presents the projected costs by installing the Spectrum RIM and highlights comparative areas of savings over a 10 year period of costs by modality, technical costs and staffing requirements as defined in Phase I. The model also projects net cash flow requirements and assumptions on which the model is calculated. Following is a graph of comparative professional staffing levels and technical costs taken from the Executive Summary of Phase II for one of the hospitals participating in the clinical evaluation program.



COMPARISON OF MD'S FULL TIME EQUIVALENTS COMMITTED TO THE INFO / IMAGE MANAGEMENT WHEN THE PROPOSED IBM-PCS RIM SYSTEM IS INSTALLED (SOLID BARS) VERSUS PRESENT MANUAL SYSTEM (SHADED BARS).



COMPARISON OF THE FIRST YEAR TECHNICAL COSTS OF PROPOSED IBM-PCS RIM SYSTEM (SOLID BARS) WITH THE PRESENT (SHADED BARS) MANUAL MANAGEMENT OF RADIOLOGY INFORMATION (in \$1000's).

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PC Extensions to a Radiology Information System

Murray G. Baron, Doris S. Strange and Jeffrey A. Hendricks

Department of Radiology, Emory University School of Medicine,
Atlanta, GA and Apple Computer, Inc.

No Radiology Information System currently on the market is perfect, nor can any one product be expected to be all things to all institutions. Although the better programs, for the most part, provide the needed functionality, the implementations are quite different and, at times, more closely resemble a computer engineer's concept of an X-ray department than actual practice. Because of their size and complexity, these programs are relatively inflexible and are difficult to change to suit departmental requirements. The "tailoring" that is allowed for newly purchased systems tends to be simply cosmetic in nature. Furthermore, the large firms that produce these programs, such as IBM, DEC, etc. are loathe to admit faults in program design and even once they do, it is a matter of months or years before the corrections are incorporated in the next upgrade.

With proper networking, however, it is possible to correct many of these awkward or faulty processes and actually extend the capabilities of the program by offloading functions from the central computer and then altering them as needed. For these purposes, data is sent from the host computer, which now acts as a file server, to one or more PCs for further manipulation and, if desired, independent output. Usually, only minimal programming of the PC is required because of the availability of a wealth of reasonably priced software that can provide almost any desired function. The inviolable rule for these procedures, however, is that

whatever is done cannot affect the code of the management system or alter its database. If this is not adhered to, maintenance of the management system becomes almost impossible and software support contracts are voided. This can be accomplished, with DECrad, as it uses standard VMS routines for some of its processing. Data acquired at this point is completely outside of the management program.

The backbone of our information system is an Ethernet cable running DECnet. The management system runs on a VAX 785, with a VAX 780 normally used for image processing research, that is also on the network available as a redundant system. Multiple Macintosh computers are accessible across the same network. Each is equipped with an Ethernet controller board and runs TSSNet, a true DECnet emulation including both the File Access Language and the DECnet mailer. The Alisashare system allows us to use an RA90 disk drive on the VAX as storage for the PCs. With these networking tools, it is possible to exchange data and mail between the VAXen and Macintoshes in both directions.

The administrative section of the department runs on IBM PC systems and clones. A VAXStation 3100 is connected as a single node on the Ethernet cable, utilizing DEC's PC LAN/server software. The PCs are daisy chained to each other with thin wire Ethernet, which is then connected via a DESPR, a local repeater, to our backbone cable. The PCs run DOS DECnet and have the capability of exchanging mail between themselves as well as with any node on the network.

Enhancements

Once film reports and management data are archived on tape, they are difficult to retrieve in a form that is easily manipulated. This limitation applies to most of the commercially available management systems. Using a small filter program on the VAX, we are able to export demographic and administrative data from

the daily billing tape to a relational database on the Macintosh. This is now available for sorting, searching or restructuring as desired.

Archived radiology reports are also a problem. In the process of archiving to tape, all formatting characteristics are stripped. Thus, when retrieved the reports bear little resemblance to our standard radiology reports. This has been questioned by referring physicians and insurance companies. Furthermore, the sequential search required by tape storage is not optimal for the purpose. We plan to archive all outdated reports with the Macintosh and optical disks in order to give us random access and to avoid the aesthetic dropout.

With our management system, it is not possible to access more than one online X-ray report in an efficient manner. This can be corrected by copying the patients X-ray history onto the Macintosh, thus providing a list of examination ID numbers. Utilizing a split screen, any number of individual reports can then be called up in random fashion.

The PCs are also used to maintain individual, specialized databases for the various sections in the department. The customized database programs run on Macintoshes but the data files are kept on the VAX because of the large available storage space and the convenience of doing only one backup a night and securing all data. We also are using the PCs for generation of mammography reports and are in the process of extending this capability to other fields such as angiocardiology, nuclear medicine and, possibly, bone radiology.

Utilizing the graphical capabilities of the Macintosh, we have demonstrated the feasibility of capturing digital images from the network and adding them to the printed radiology report. It is also possible, if the images are read off the Macintosh screen, to add arrows and numbers during interpretation, with almost no extra effort required of the radiologist, and so produce an annotated report.

The Entity-Attribute-Value Data Model in Radiology Informatics

Carl D. Niedner

Digital Equipment Corporation, Marlboro, MA

Introduction

This paper describes the entity-attribute-value model for data and procedure, a model which offers some promise for the solution of radiology integration problems. The model's merits are discussed in terms of its potential ability to integrate data types common in radiology, and to solve three specific integration problems. Examples and rough benchmark statistics from the VAX DECrad V4.0 product are reported.

Radiology Informatics' Current Problems

Need for Integration: The most important challenge currently facing the field of radiology informatics is the need for integration. Though specialized radiology applications continue to make and require functional improvements, their individual sophistication currently far outstrips their aggregate ability to provide a unified environment for the practice of radiology. Progress in this arena is being made, primarily through the development of standardized interfaces [3], [6] but no dominant integration strategy has yet emerged. Despite such efforts, the importance of integration continues to increase. Both competitive pressure on hospitals and the increasing complexity of specific applications contribute to this trend. The anticipated trend toward patient-centered hospital integration [10] will result in further pressure not only to integrate the radiology department, but also for radiology components and systems to adapt to and support the needs of an overall integrated healthcare computing environment.

In addition to the clear need for integration, radiology informatics also needs to provide greater flexibility than is now the norm in specific applications such as information systems. In particular, users of radiology computing systems require improved abilities to specify the details of their systems' operation.

In addition to meeting the foregoing needs, any strategy for integration in radiology must account for those areas of technology whose ongoing rapid development will most significantly affect the field: image storage, retrieval and manipulation capabilities [9], computer assistance in diagnosis and treatment, automated processing of

text [5], and applications of neural networks [3].

Generic Needs: At a low level, the requirements described above may be summarized as the need for an integrated environment which handles disparate data types in a homogeneous fashion. The most important of these types encountered in radiology are as follows:

1. image - bitmap representations of medical images, subject to high-speed recall, presentation and manipulation;
2. discrete - data which fit the traditional database model, wherein data is categorized into fields and records, such that every field within a particular record has a unique value;
3. numeric - discrete data upon which calculations may be performed;
4. text - radiologic findings comprise the most important application of this data class, but their use permeates radiological computing, including diagnosis and procedure summaries, coded titles, incident reports and numerous other examples.

There are numerous data types encountered in radiology which do not fit clearly into these categories, and there are also numerous structures which consist of hybrids of more than one basic data category. The low-level integration of these basic data types is a prerequisite for any overall radiology integration strategy.

Example Problems: At a higher level, integration in radiology consists of a number of complex and interrelated problems, not all of which have yet been clearly defined or even identified. This paper will consider simple cases of three such problems: (1) interfaces between Picture Archiving and Communication Systems (PACS) and Radiology Information Systems (RIS), (2) integration of radiological text, numeric and discrete data, and (3) automated text analysis. The following sections propose a low-level data and functional model for radiology integration, and evaluate its theoretical merits on the basis of both these example problems and the low-level requirements stated above.

The Entity-Attribute-Value Model

The entity-attribute-value (EAV) model is a method of representing knowledge of the types traditionally called data and procedure in a homogeneous form. This form consists of a three-level hierarchy containing entities, attributes and values, in that order of significance. Data is randomly accessible via indices at each hierarchical level.

Entities are the subjects of information or knowledge stored in an EAV database. Attributes are properties by which information about entities is organized. Values are the specific data stored. The unique combination of an entity, attribute and value ("EAV tuple") represents a fact. For example, the idea represented in English by "An apple is red in color" may be represented as the EAV tuple <APPLE|COLOR|RED>. (For the remainder of this paper, angle brackets will delimit EAV tuple examples; entities, attributes and values will appear in order, delimited by the "|" character). By their hierarchical nature, EAV databases ensure that all data concerning a particular subject (entity) are grouped together in a defined order, and within a subject, that all values for a given property (attribute) are grouped together in similar fashion. Thus, in an EAV database, knowing an entity, one can immediately retrieve a list of attributes which pertain to that entity. For any entity and pertinent attribute, one can similarly retrieve a list of values. An entity-attribute combination may have more than one value. For example, the entity APPLE might have both values RED and GREEN for attribute COLOR. It is important to note that EAV data structures are recursive: i.e., that an element (entity, attribute or value) of a tuple may itself be a tuple.

Figure 1a: Relational Database Example

ACC	EXAM	DATE	DX1	DX2	DX3	DXTXT
123	CH1	6/5/90	786.50	410.1		CHEST PAIN, SUSPECT MI
456	USTHO	6/10/90	482.9			BACTERIAL PNEUMONIA

Traditional databases indicate the significance (attribute) of a data item (value) to the record (entity) in which it occurs via the item's physical location. Figure 1a provides an example of a traditional database which might be used in a radiology application.

Figure 1b: EAV Representation

```
<123|DATE|6/5/90>
  |DX1|410.1>
    |786.50>
      |DX|TEXT|CHEST PAIN, SUSPECT MI>
        |EXAM|CH1>
<456|DATE|6/10/90>
  |DX1|482.9>
    |DX|TXT|BACTERIAL PNEUMONIA>
      |EXAM|USTHO>
```

EAV databases, on the other hand, represent the relationship between entities and values directly via the attributes. The database shown above might be represented by the EAV tuples presented in Figure 1b. Note that empty "fields" are not stored in the EAV representation. The relational model offers an economy over the EAV example in that attributes in the relational model are implied by position, and do not need to be represented directly. Use of key compression techniques, and the model's ability to avoid storage of placeholders for missing data will enable EAV-model databases partially to offset this shortcoming.

It is possible to construct variants of the EAV model which retain its essential characteristics. The prototype EAV implementation associated with VAX DECrad V4.0, further discussed in the Appendix, makes use of a four-member EAV tuple. The first three members of this tuple correspond exactly to the EAV model as presented above. The fourth member is designated as "text" or "comment," corresponds one-to-one with an associated value, and is not indexed. This scheme permits efficient storage of large atomic data structures such as text blocks.

Standard databases allow direct access to records (entities) via indexed "key fields." Access to records via non-key values requires either searching an entire database and filtering out unneeded data, or maintenance of cross-reference indices for any non-key fields by which users wish to select data. EAV-model databases are subject to the same limitations, but the model permits cross-reference indices and other standard (and nonstandard) database constructs to be integrated into the same homogeneous architecture as the main database, with resulting gains in simplicity, uniformity and flexibility. The mechanics whereby this integration is accomplished are presented in the following sections.

Applications to Radiology Computing

Low Level Constructs: The EAV model is amenable to the development of a wide range of tools necessary for an integrated radiology environment. It is productive to consider these applications first at the lowest level, then consider how low-level EAV tools might be used to solve practical problems of radiological integration.

The most basic task within an integrated radiology environment will be to provide those services currently performed by traditional database technology. The preceding section has explained how a traditional database (using a relational example) might be implemented under an EAV model, but has not treated the implementation of such ancillary data structures as inverted keys. Implementation of these structures is relatively straightforward under the EAV model. Cross-references may be implemented by assigning a unique cross-reference entity to every attribute to be inverted. For every instance of that attribute in an EAV tuple, a corresponding tuple consisting respectively of the cross-reference entity, the original value and original entity is stored. This procedure enables rapid retrieval of lists of entities which exhibit a particular attribute and value.

Consider the example attribute COLOR, and suppose that it has been assigned the cross-reference entity COLOR-XREF. Then the tuple <APPLE|COLOR|RED> will be inverted as <COLOR-XREF|APPLE|RED>. Traversal of the subtree <COLOR-XREF|RED... will retrieve APPLE, as well as all other entities red in color. Traversal of the subtree <COLOR-XREF|... will retrieve a list of all colors which have been used to describe entities in the database.

The implementation of list structure, a fundamental building block of classical artificial intelligence (AI) [1] has been presented implicitly in the preceding example. Lists are simply EAV tuples with one or more elements unbound. For example, <COLOR-XREF|PURPLE|... (entity and attribute bound, value unbound) represents the list of all things purple in color. A use of list structure applicable to the current example would be to reserve a special entity to contain lists of attributes and their cross references, e.g.: <XREF-LIST|COLOR|COLOR-XREF>

|SHAPE|SHAPE-XREF>

|TASTE|TASTE-XREF>... Such a list

will enable an application to determine an attribute's cross-reference entity rapidly.

The preceding example also implicitly presents another important property of EAV databases: that cross-references are combinations of method and data structure. EAV databases differ from their traditional counterparts in that the methods by which cross-references are created and maintained may be represented within the same homogeneous structure which contains both database and cross-references. This integration is achieved by the implementation of rule processing within the EAV software.

Rule processing within the EAV model may be achieved by developing a method for identifying certain classes of EAV tuples as rule hypotheses, and assigning to each hypothesis tuple one or more "conclusion" tuples, whose assertion (storage) is to be caused by the assertion of the hypothesis. This method has been applied with some success to VAX DECrad V4.0's Case Indexing functions, as described in the Appendix. Under this method, a specific entity is reserved for storage of rule information. Under this entity, the attributes consist of hypothesis tuples, and the values of conclusion tuples. For optimum performance, hypothesis recognition depends most significantly upon a constant element of the tuple (attribute in DECrad's case), then optionally on another element (value in DECrad). Hypothesis tuples are reorganized so that their recognition elements occur first, to enable rapid retrieval by the recognition elements. This implementation of rule processing also requires a means for representing unbound elements in both hypothesis and conclusion tuples. The convention used in DECrad's EAV implementation (and for the remainder of this paper) represents universal quantification ("for all" or "for any") with square brackets ("[]") and definite quantification (replacement of a previously unbound value) with braces ("{}"). Under this scheme, <RULE|<SIZE|BIG|[X]|<[X]|WEIGHT|HEAVY>> represents the rule expressed in English as "for any X, 'X is large in size' implies 'X is heavy.'" Clearly, additional rule-processing tools such as Boolean and probabilistic operations on hypotheses, and more sophisticated binding techniques are required for applications which are to approximate reasoning, but even the simple tools described are sufficient to represent effectively the methods necessary for database cross-referencing. For example, the rule <RULE|<COLOR|RED|[X]|<[X]|COLOR-XREF|RED|[X]|>> expresses the cross-reference method exemplified earlier. Since EAV tuples are recursive, methods can be generalized:

<RULE|NATURE|ATTRIBUTE|X|><RULE|<X|A|B|><X|-XREF|A|B|>>>, for example, represents a general rule for creating cross-reference entities and rules.

Another important aspect of EAV structures is their ability to represent algorithms, both in traditional forms, and in forms such as goal trees favored by artificial intelligence applications [1]. Traditional algorithms may be represented in simple sequential manner, by using values to indicate both step sequence and operations to be performed. Alternately, hierarchical modular structure may be expressed by nesting of tuples or by recursion in which values or portions thereof recursively indicate other entities ("value-entity recursion"). Goal trees are also easily represented using value-entity recursion. Such algorithm representations require two features in order to be used by application software: links from elements in the algorithm representation which denote actions to the software objects which perform the actions, and a method of invocation for algorithms so represented. Possibly the simplest invocation method involves assertion of an EAV tuple containing the algorithm representation. Under this method, a linguistic means must be provided to suppress the storage of asserted tuples; otherwise, flow of algorithms may result in spurious effects in EAV database structures.

This type of recursion may also be used in constructing augmented transition networks, which are important tools used by applications attempting to parse natural language texts [1]. Charniak [1] defines such networks (ATNs) as transition networks (directed graphs whose arcs are designated as tests of words for their parts of speech [1]) with three adjuncts: (a) a data structure containing the current parsing history; (b) a structure specifying atomic operations on sentence constituents (e.g., converting singular to plural); and (c) structures specifying methods for creating, inserting an deleting constituents. Directed graphs with labeled arcs may be constructed relatively simply using value-entity recursion. Structure (a) above may be implemented from traditional database and list components, and (b) and (c) as goal trees. Thus an entire ATN may be represented within the context of an EAV structure.

EAV In Radiological Examples: The previous section has described how several low-level constructs of great importance in AI and traditional applications may be constructed using the EAV model. This section will describe how these constructs may be applied to solve the example radiology integration problems presented in the introduction.

Integration of disparate data types: The first such example concerns the integration of functions currently performed by a traditional RIS. Most commercially available RISs currently use traditional database technology to store their data. Such systems suffer from the drawback that retrieving database subsets requires passing through an entire database, restricting by a limited number of inversion keys, or custom programming. It is relatively easy to construct a software interface which equates the traditional database representation of data used by an RIS with an EAV representa-

tion, and automatically calls a generic EAV assertion routine to "echo" storage of traditional RIS data in the EAV structure. A simple interface of this type has been included in VAX DECrad V4.0. This interface echoes the storage of a subset of the RIS database (contents of the subset are specifiable by system managers) in an EAV structure. All attributes corresponding to fields defined in the RIS dictionary have cross-reference entities defined by a generic rule of the form given in the previous section. Text blocks stored in the conventional RIS are parsed into individual words, which are asserted as values for specialized text attributes. At present, the only database-correspondent entities in the EAV structure are radiology examination identifiers (accession numbers), although the system is easily extensible to include other entity types such as patients, personnel, resources, and others. The homogeneous inversion structure enables users to retrieve data based upon extremely flexible combinations of attribute/value criteria. These structures also make optimization of such inquiries almost trivial. For example, development of a query to find all cases with diagnostic reports containing one of a number of alternative phrases, for patients born within a specific year, exhibiting one of several complaints, is a simple process, requiring no programming, of constructing and evaluating simple, verifiable subqueries, and assembling them into the completed query. Another simple interface permits RIS users to perform a subset of RIS functions upon retrieved lists of entities.

PACS-RIS interfaces: The second example problem presented in the introduction involves the specification of a PACS-RIS interface. A number of vendors and institutions have devoted and continue to devote enormous efforts to this problem [7], [6], but no definite solution has yet emerged. The Marburg Model, [7] upon which much of this work is based, postulates that PACS-RIS interfaces may be achieved by analyzing an entire radiology operation into component functions, and specifying the interfaces between these functions. Some of these interfaces are currently performed by RIS, others by PACS, and others, as yet undefined, will constitute the interface. Greinacher *et al.* use the Marburg Model to build a unified data model of radiology based upon entities and their relationship to one another[6]. They then continue by specifying typical entities and attributes encountered in radiology. The entities so specified are the fundamental conceptual units upon which interfaces may be built. EAV constructs are suitable for representing both the overall and detailed models developed by Greinacher *et al.* Their detailed model is expressed in EAV terms in its definition. The overall model, represented as a directed graph connecting entities and relations, may be represented quite simply in EAV structure using value-entity recursion. The interfaces themselves may communicate data using a nested entity-attribute-value format. Under such a scheme, a transaction might contain a single entity, then one or more attribute-value pairs (called "name-value pairs" in other literature, e.g. [3]) to specify data pertinent to the indicated entity. For economy, any attribute for which multiple values were transmitted might be transmitted only with the initial value, and its repetition for the remaining values could then be implied by space-saving device. Such interfaces may be gaining acceptance in the general field of medical informatics [3]. Another way in which the

EAV model might benefit such interfaces is by increasing their flexibility. Current interfaces, both internal and external to radiology, tend to feature event-triggered information transactions [3]. The triggering mechanisms which associate events in host systems with the transactions they cause are typically hard-coded in the software of the host systems. This situation leads to extreme inflexibility of interfaces: difficulty of customization, and diversion of software development resources to engineering and support of hard-coded interfaces. One approach to this problem involves recognizing event-triggered transactions as a special case of query output. In such an approach, queries must be able to specify temporal and other conditions under which the query is to be evaluated, as well as information constraints currently supported by most query software. A typical query under a system currently in operation might be rendered as "retrieve and transmit patient names, responsible physicians and diagnoses for all chest studies performed within the last 36 hours." A query capable of specifying trigger events might be rendered as "From now until further notice, whenever a chest exam is performed, retrieve and transmit patient name, responsible physician and diagnosis." By virtue of the homogeneity with which it represents data, the EAV model is suitable for expressing such queries. By virtue of its ability to represent retrieval methods (goal trees) and discrete procedures (traditional algorithms), it is also suitable for evaluating them.

Automated text content extraction: The third example problem posed in the introduction concerns automated parsing and extraction of semantic content from radiologic texts, and integrating such information with other radiological data. Promising work in this area is currently being conducted and reported by Gabrieli and Speth, among others [5]. Their work involves processing medical texts, and representing facts contained in them in an hierarchical coding system. It is expected that the importance of such sub-applications will increase dramatically in the near future [10]. The EAV model will prove quite useful in this area as well as those described previously, due to several factors: (1) the ease with which it may be used to represent ATNs and other constructs used in natural language processing; (2) its ability to represent knowledge in a simple, intuitive, recursive form, which will lend itself to representation of semantic content; (3) its facility for storing hierarchical fact codifications of the type used by Gabrieli and Speth; and (4) its ability to integrate these features with traditional methodologies and structures as well as functions yet to be developed.

Impact of Emerging Technology: In evaluating the viability of any proposed model, it is necessary to assess its ability to react favorably to foreseeable developments in its surrounding environment. An extremely significant trend in modern computing is the development of massively parallel hardware architectures and the associated evolution of software concepts. One such concept which is rapidly gaining importance is the neural network or "connection model." Neural networks have recently received considerable attention as computing structures, and appear to offer considerable benefits to the solution of a number of problems including visual

pattern recognition and learning [4], and solution of complex diagnostic problems [8]. Based upon theoretical models of the human central nervous system, they specify computational structures as networks of simple nodes which operate at various states of "excitement." The activity of any node in such a network may potentially either excite or inhibit the activity of other nodes. Such networks may be represented as directed graphs with weighted arcs as exemplified in Figure 2a. Current neural theory finds it useful to represent such networks in matrix form. The matrix representation of the example network is shown in Figure 2b. Matrix representations of such networks are useful for simulating learning and response to stimuli via matrix multiplication [4]. Representation and manipulation of neural networks in EAV structures is again relatively simple. The neural net depicted in figures 2a and 2b may be represented by the EAV tuples $\langle A|B|-10 \rangle$, $\langle A|C|+3 \rangle$, $\langle B|A|+7 \rangle$, $\langle C|A|+5 \rangle$, $\langle C|B|-6 \rangle$, $\langle D|A|-6 \rangle$, and $\langle D|B|+4 \rangle$. Again, the EAV model's ability to avoid storage of placeholders for missing data give it a decided economic advantage over the matrix model, especially in large-scale cases which are especially sparse (cases with large numbers of nodes, where each node is connected to relatively few other nodes), which may account for a large portion of neural net applications. This economy will apply to processing times in such cases as well as storage requirements; assuming a system of m nodes, each connected, on average, to c other nodes, the matrix model will require m^3 multiplication operations to complete a learning or recognition event, while the EAV model will require mc^2 . D'Autrechy *et al.* have used a structure quite similar to EAV with advantage to represent neural networks in the MIRRORS/II project [2].

Figure 2a: A Neural Network

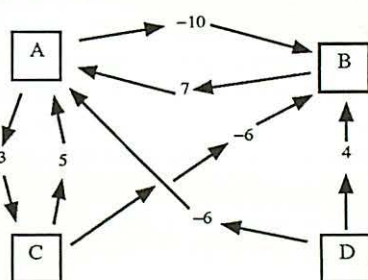


Figure 2b: Matrix Form To:

From:	A	B	C	D
A	+10	-10	+3	0
B	+7	+10	0	0
C	+5	-6	+10	0
D	-6	+4	0	+10

Summary

The entity-attribute-value model displays considerable promise for solution of integration problems in radiology informatics. This potential is the effect of several useful properties: (1) the model's ability to accommodate traditional database methods, low-level AI structures, and control structures; (2) the ease with which it may be integrated with existing applications; (3) its adaptability to such emerging computing technologies as neural networks, and (4) the simplicity, uniformity and flexibility which result from the homogeneous implementation of all of these elements.

In order to achieve the level of integration required by the increasingly sophisticated radiology environment, the field of radiology informatics will need to pursue unified architectures and data models such as EAV. Although this model is potentially useful in its own right, it is presented here to inspire thought and discussion of such models and architectures in general.

Appendix: EAV in VAX DECrad V4.0

The development of the Case Indexing features of Digital Equipment Corporation's VAX DECrad V4.0 product has provided a productive test of some of the concepts discussed in this paper. VAX DECrad is implemented in the Digital Standard MUMPS (VAX DSM) language and database environment. The Case Indexing features offer radiology personnel the opportunity to retrieve exams rapidly from the DECrad database according to flexible criteria on homogeneous attributes, and to perform selected DECrad functions on the retrieved exams. The primary users of these features are expected to be radiologists developing interesting case files, administrators tracking service quality, and film librarians. A number of facts concerning the development of these features are summarized in the following list:

1. The phases of the implementation required roughly the following allocations of FTE personnel: general design, 12 days; prototype implementation, 25 days; design of revisions and extensions, 3 days; implementation of revisions, 45 days; quality assurance and associated revisions, 25 days; technical documentation, 12 days; user documentation, 40 days (total 152 days).
2. The completed prototype system comprised 60 DSM routines, 14 interactive screens, 7 fixed-format reports, and a rule-base of 30 rules (as supplied with default DECrad V4.0; the rule-base is user-extensible).
3. Benchmarks on a development system indicated that activation of all possible EAV options at a large (1000 diagnostic reports per day) radiology site would consume approximately 7% of one VAX Unit of Processing (VUP) in CPU resources. This benchmark was based upon an observed EAV-assertion throughput rate of 320 bytes per second on a VAX 11/780, and an average estimated EAV assertion volume per exam of 1900 bytes (tests conducted at the University of Massachusetts Medical Center found mean diagnostic report sizes of 580 (SD 520) bytes).

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Development of a Product Inventory System for a Diagnostic Imaging Department

Alicia Giangrande and Michael Taricani

Yale-New Haven Hospital,
New Haven, CT

The delivery of diagnostic and therapeutic imaging services demands that a medical product inventory be readily available. For our department over 80% of product inventory occurs in Special Procedures which consists of a Cardiac Catheterization Laboratory and a Peripheral Vascular Interventional Laboratory. Between the two laboratories about 1200 different items are used with an inventory of about 5000. Inventory management and the ordering process can be a time-consuming task. In this paper, we would like to share with you our experience in developing an inventory control computer system to help manage product ordering.

Our inventory system had three main objectives. We wanted the system to keep track of shelf numbers and print a daily list of items to order. With a system that stores item usage, we also wanted to reduce on-shelf inventory especially underutilized or unpopular items. The system, which was to duplicate our manual card-requisition system, also was to provide statistical data concerning number of items used, inventory value and budgetary projections. Our second objective was to choose a database that could easily handle changes and was relatively inexpensive. Our third objective was to create a system that was easy to use so that technologists could continue their responsibility of product ordering. Having had experience with Q&A and knowing it was easy to use and inexpensive, we decided to choose it as our database software.

Our first task was to develop a coding scheme for each inventory item. The codes needed to be easily recognized within a 10 character limit. The codes in the inventory system correspond to the codes used for billing in our Radiology Information System (RIS). The first character identifies each distinct budgetary department. In this case S is used for Specials. The second character identifies the subdepartment which is either a C for Cardiac or a P for Peripheral. The following characters in both the Cardiac and Peripheral groups further identifies the product by specifying the technique for which it is used and/or the size, product type and style. As an example, a cardiac adult angioplasty balloon of 1.5 french size and "Skinny" style is identified as SCAAB1.5SK. By logically grouping products we are able to retrieve a product record by using a partial lookup. For example, we can retrieve all product records which are adult angioplasty balloons of 1.5 size. In addition, a sort by codes categorizes records so that comparisons can more readily be made. In the end, we had 1200 items coded with 40% of those items from the Cardiac section and 60% from the Peripheral group.

Next, we developed the system's screen design. This has undergone several changes. Figure 1 shows our most recent design. The initial screen is divided into three parts. The first part contains user and product information. As a security precaution, a user must enter their initials along with their password to enter the system. The record or "card" for each inventory product keeps track of the current and previous user. In this way, if entered data is in question we can better resolve the issue. The product information includes the product code which uniquely identifies each item as well as its group (SCAAB., SPT., SCAOG.), catalog number, description, price per item, vendor, date of inventory startup, startup inventory number as well as a Y/N field for product specifications. The starting inventory number is used later in the "Summary of Product Use". The product specification field is a cursor control field which allows the user to skip to the bottom of the last screen so that one can view product specifications.

The next part of the screen shows the total number of items used, ordered and received as well as the number of items still on order. These are calculated fields. Items used are updated on a daily basis from a flat file which is downloaded from the RIS via Kermit into the PC. A download contains those items charged in the RIS the previous day with Monday containing items charged Friday as well as the weekend. The download file is then imported into Q&A and the individual product records are updated by matching product codes. The Total Ordered and Total Received fields are the addition of individual ordered and received entries which are subsequent system screens. (Please see Figure 1). We believe that the most heavily used product will need at most about twenty-five order and receive slots. Thus in the databases for Cardiac and Peripheral we hope to store one year of inventory data. The field out-on-order is calculated by subtracting the Total Received from the Total Ordered. In theory, all that is ordered under a Purchase Order (PO) number should be received. The YTD cost is the Item Price multiplied by the Total Used.

The last part of the screen is a "Summary of Product Use". The Shelf Stock describes the number of items on the shelf. This is calculated as Total Received minus Total Used plus the Starting Inventory Number. The Received-Used-Par field is a relationship that describes the difference between received and used in relation to the user-defined par level. The next field describes the number of items to order. It is the addition of the previously described relationship number (Received-Used-Par) with the starting inventory number (Start Inv) and the amount out-on-order (Out on Order). The amount to order is the opposite of the result of this calculation.

The system works well. All pertinent information concerning a product appears on the first screen. There is a sufficient user audit trail and a security feature that prompts a user for a password. In addition, we have an error log that records any codes from RIS that are not found in the PC database. In this way we can keep the PC and RIS codes in synchronization. Examples of inventory reports are shown in Figures 2 and 3. Figure 2 shows the TO ORDER report which prints after a download occurs. A

technologist reviews this list and places necessary orders. Figure 3 is a sample management report that shows utilization and YTD costs.

An issue we have encountered with the system has been human error in recording items used during a procedure and items that are received and/or ordered. In all three circumstances either forgetting to enter the information, using an incorrect code, miscounting numbers received or ordered, and/or mistakenly altering data will affect system inventory levels. Overall the computer system has been very helpful and has taught us about our inventory and its usage.

In conclusion, we have a few recommendations and we would like to share with you a few issues that we are currently exploring. We recommend that inventory especially of frequently used items should be periodically counted and the system updated to account for discrepancies. In addition, we favor manufacturer printing of barcode labels on products. It is hoped that coding for these labels will show some consistency and logic between manufacturers. Barcode wandling can reduce key punching; however, there is the issue of getting the correct label on a product and, once a label is printed, finding a suitable location to stick it. This last issue is especially a concern with smaller individually packed items.

There are two issues we are currently exploring. We believe that since we have an appropriate number of items on the shelf and we are comfortable with our par level settings, we believe a weekly versus a daily download will be sufficient. The second issue is to have the system provide some notification of increased usages so that we can correspondingly increase a product's par level. In this way, we can better control our on-shelf item numbers.

FIGURES

```

-----DIAGNOSTIC IMAGING INVENTORY SYSTEM-----
:OPERATOR:                LAST USER: MIKE TARICANI          DATE: 04/17/90      :
:PRODUCT CODE: SCAAB1.5SK  CATALOG NUMBER: 01678-06         :
:DESCRIPTION: 1.5 20/1.5 Skinny Balloon                      PRICE   : $595.00    :
:VENDOR: SCIMED            DATE STARTED: 04/06/90            START INV: 3      :
:PRODUCT SPECIFICATIONS(Y/N):                               : 0              :
:-----:
:EDIT USED(Y/N):                TOTAL ORDERED : 1            :DEC CHARGE :
:NUMBER      : 0                TOTAL RECEIVED: 0            :YTD COST   : $595.00
:TOTAL USED   : 0                OUT ON ORDER  : 1              :
:-----:
:      **SUMMARY OF PRODUCT USE**
:SHelf STOCK: 3                RECEIVED-USED-PAR: -4
:PAR LEVEL   : 4                PLUS S.I. + 0.0. : 0            : ORDER: 0
:-----:
:  P.O.      :  ORDER   :  AMOUNT   :  AMOUNT   :  RECEIVED
:  NUMBER    :  DATE     :  ORDERED  :  RECEIVED  :  DATE
:  M         :  04/06/90   :  1        :             :
:  :         :  :           :  :         :  :
:  :         :  :           :  :         :  :
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:  :         :  :           :  :         :  :
:  :         :  :           :  :         :  :
:-----:
:OUTER DIA.:                LENGTH:          ATH:          BALLOON LENGTH:
:INNER DIA.:                NUMBER OF SIDEHOLES :          BALLOON DIAM. :
:BLANKET(Y/N):              RECEIVE DATE:
:-----:

```

Figure 1. Inventory Screen Design.

04/17/90					
CARDIAC CATH LAB					
DAILY ORDER LIST					
VENDOR	Product Code	CATALOG NUMBER	DESCRIPTION	Shelf Stock	ORDER
-----	-----	-----	-----	-----	-----
CORDIS	SCAAB2.00R	525-420	2.0 ORION BALLOON	8	1
SCHWEIDER	SCAAB3.0WR	P-33-030	3.0 MONORAIL BALLOON	5	1
SCIMED	SCAAB35SKB	02229-04	3.5 SKINNY .018	3	2

Figure 2. The daily TO ORDER report.

CARDIAC CATH LAB			
COST OF BALLOONS ORDERED			
TOTAL USED	TOTAL ORDERED	BALLOON TYPE	\$ SPENT ON BALLOONS
-----	-----	-----	-----
32	22	SCAAB3.0S2	\$12,540.000
	9	SCAAB3.0S3	\$5,850.000
31	30	SCAAB3.5S3	\$19,500.000
24	21	SCAAB3.0SK	\$12,180.000
20	24	SCAAB2.5AC	\$16,200.000
19	4	SCAAB2.5S3	\$2,600.000
	8	SCAAB2.0S3	\$5,200.000
12	7	SCAAB3.5SK	\$4,165.000

Figure 3. A sample management report.

Rearrangement Management Information Facilities (RMIF)

P.J.S. Boon

Academic Hospital Maastrich, THE NETHERLANDS

Summary

In the Netherlands the focus on Management Information Systems, within the (academic) hospital environment, has strongly been intensified. This has led to several new initiatives, from which the here described one is from the Academic Hospital in Maastricht: a joined project together with Digital Equipment Corporation.

This initiative is based on the principle that data, which has already been collected on a routine base, could serve as feeder(s) for the wanted necessary Management Information.

Introduction

The Academic Hospital in Maastricht (AZM) has worked four years already with the hospital system of BAZIS. BAZIS is a fully integrated HIS that was made to support the operational processes like for example: general ledger, laboratory research, patient care and nursing.

The BAZIS system does not provide so far any adequate Management Information tool. Due to the process-character of BAZIS it is extremely difficult and labor-intensive to collect this information, and select or aggregate it.

Within AZM, together with Digital Equipment Corporation, a project has been formulated and started with the name RMIF (Rearranging Management Information Facilities) that must develop a MIS for middle- and top-management. This new system should provide in a quick and easy way answers to management questions and should also make it possible for them to calculate alternative strategies.

In the first project phase (which was finished last autumn) the decision was made to start with a separate computer-system (from BAZIS), which has to be loaded with data from the BAZIS-system and equipped with a so-called 4GL-tool. With this, an end-user could get his wanted information at any time of the day without heavy load on the BAZIS-system.

Today's situation

The biggest problem with today's MIS is that the wanted information is not clearly and properly defined and the occurrence of a lot of changes during the problem definition-phase. Frequently this information is clustered from different minor database-resources, throughout the various process-system parts of BAZIS. These resources could contain some million records, so that proposed actions could take some hours cpu-time.

In practice the wanted actions are like:

- there is a specific need of information
- this information need should be described carefully
- as next, it should be investigated from which system-resource this information should be withdrawn. This happens momentarily with a (third generation) programming tool with extra features. This work is frequently intensive and normally not planned; it runs therefore through all daily activities, creating unexpected delays. This problem should be resolved of course organizationally (which is however not always the case)
- when everything is tested adequately, it could be re-routed to the BAZIS-machine, after which a batchprocess could be planned. When this information is needed more frequently, there is also a need of written operator-guidelines.

It is quite obvious that this working scheme is troublesome and gives unacceptable turnaround-times.

Solution

To find a solution for this problem, there has been chosen for a (separate) stand-alone computersystem, which looks like: (see Figure 1)

- DEC microVAX 3800 with 16Mb internal memory
- system disk (RA70) with 280 Mb
- application disk (RA90) with 1,2 Gb
- tape cartridge (TK70) with 296 Mb
- tape unit (TSV05) 1600 bpi
- 7 VT320 displays
- LNO3AH laserprinter

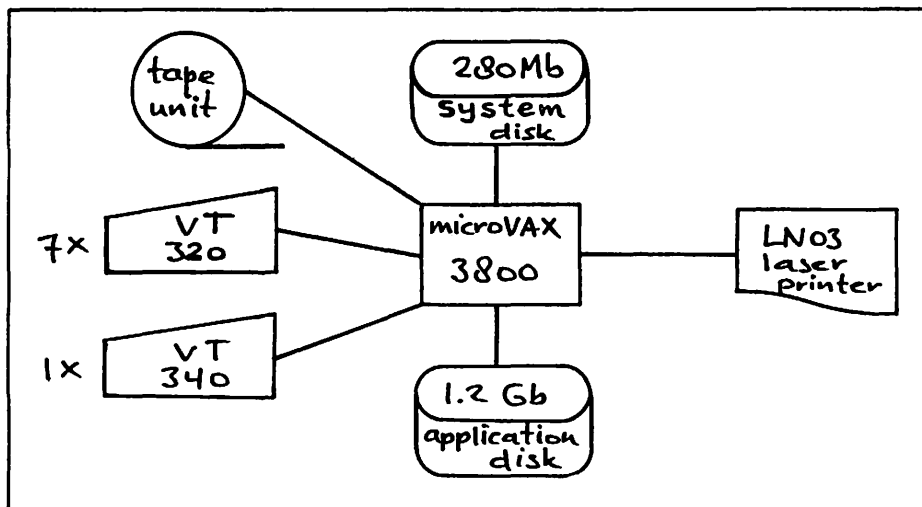


Figure 1.

This system should be loaded periodically, with the help of special developed programs, with data. The system should be available the whole day and equipped with 4GL tools, so that the end-user could extract his desired data himself.

The software-configuration looks like: (see Figure 2)

- VMS Operating System (1 - 20 users)
- VAX/RdB relational database system (including SQL)
- CDD common data dictionary (backup of metadata)
- VAX/RALLY 4GL (application) tool
- TEAMDATA 4GL (query) tool
- PASCAL compiler, (RdB precompiler included)

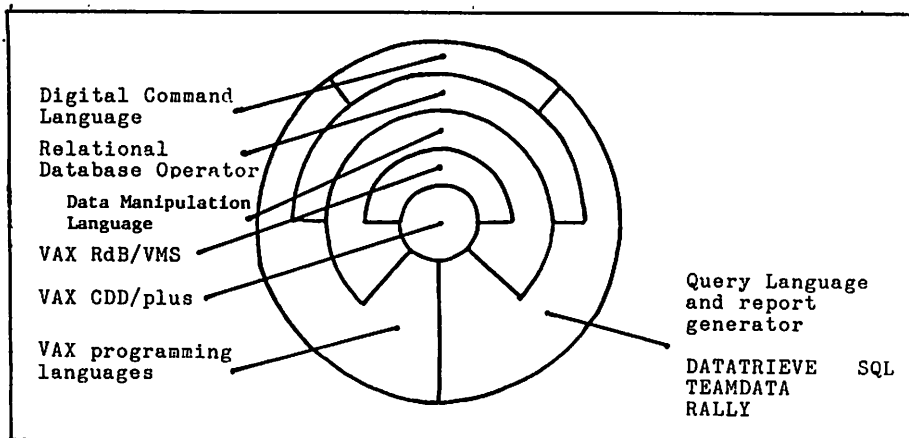


Figure 2.

Further programs have been developed with PASCAL, for example; to read data from tape and store it (eventually after some specific conversions) into the Rdb.

This method of providing information, follows the current trend, where the user is more and more involved in the automation process: at one side he is much more qualified and on the other hand the available tools will serve him better.

Project result

In the current BAZIS environment a study has been started to determine which source-databases are needed to load the RMIF-database (see Figure 3). This loading is being performed with 3GL tools because frequently conversions are necessary and with 4GL this would take far too much time.

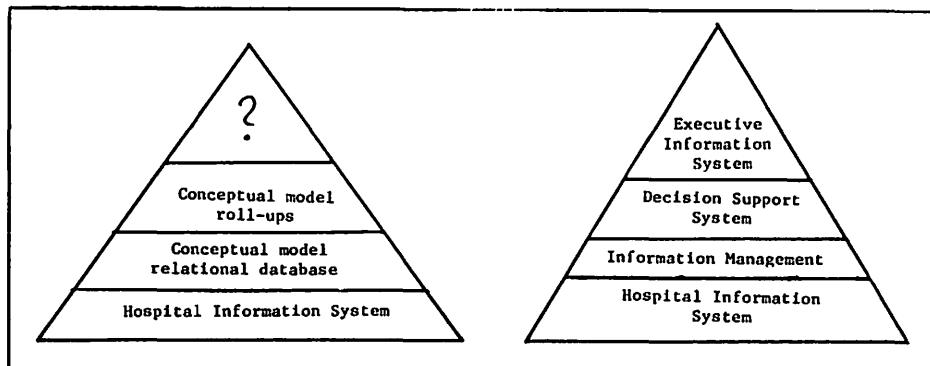


Figure 3.

These load- and conversion-programs are written in a flexible way so that these could be used for all wanted databases. Because source databases in the RMIF sphere are huge and numerous, this has led to two problems:

- with the commonly used 4GL it is impossible to aggregate, in an easy way, more databases and procedures into a nice overview. (The user is far too much involved in basic techniques.)
- the turn-around time with huge databases is unacceptably high.

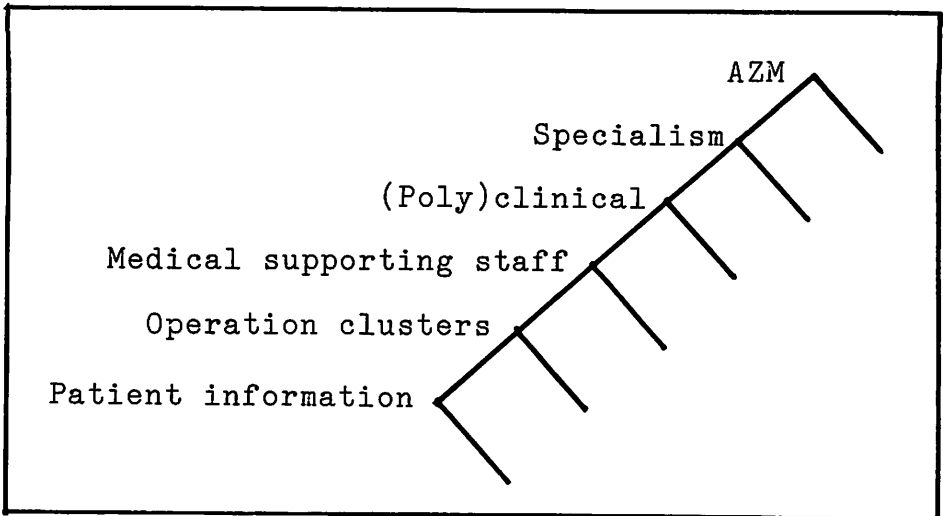


Figure 4.

The solution for these problems could be found by making or setting-up so-called roll-up-structures (see Figure 4). These are, to certain views, aggregated databases.

After this aggregation it is for the end-user then rather simple to exploit these databases with 4GL-tools.

With the help of programs, still to be created, it should be possible, within the near future, to develop easily by the end-user all needed rollup-structures, and to change or modify or to load them himself.

Conclusion

It is to be foreseen right now, that with the described above, it will be possible, at low costs, with the power of a mainframe, but with the ease and comfort of a PC, to fulfill the needs of MIS for both top- and middle-management.

Literature

Using VAX TEAMDATA
DEC No. AA-FX81B-TE

RALLY Application User's Guide
DEC No. AA-JK79A-TE

Radiology Information System Interfaces: Connecting Your RIS to the Rest of the World

Robert F. Davis

Digital Equipment Corporation, Marlboro, MA

Introduction

A stand-alone departmental system, such as a Radiology Information System (RIS), provides many advantages over software modules in an integrated hospital system. However, by definition, a stand-alone system is at a disadvantage in its ability to allow access to its data or access data from other systems.

Both the effort of re-entering data already captured and the benefit of hospital-wide, immediate access to data as it is entered, makes it necessary to connect the RIS to other hospital systems. The concept of *data integration* (or sharing data), as opposed to integrated applications, has become increasingly important as ancillary systems become more commonplace in today's healthcare environment. This paper discusses experiences with the VAX DECrad radiology system and current trends in networking an RIS to other healthcare applications. This discussion should benefit others in evaluating, planning and implementing *links* from the RIS to other computer systems.

Developing DECrad's Interfaces

The need to get patient demographic data from the Hospital Information System (HIS) became apparent at the first DECrad Version 1.0 field test site. This first interface to another system was developed as a custom feature for the site and used a simple RS-232 serial line running at 300 baud. Data messages were sent to DECrad as patients were admitted and discharged from the hospital system. The DECrad software read data records from the serial port, identified the individual data items in the record and filed the patient demographic data.

This basic concept was incorporated into DECrad Version 2.0 as a standard feature. The format was changed to fixed length data records, and several different types of ADT functions were added.

During the time that DECrad Version 3.0 was developed, the requests most often heard were for *order entry* and *results reporting*. Major enhancements in the design of DECrad's communications interfaces, necessary to implement these two functions, were:

- The ability to designate and run multiple links
- The use of different transports (RS-232, DECnet, files)
- The concept of *trigger events* within the application
- An event queuing function

The DECrad Version 3.1 release included a transaction to accept report dictation status and time from a digitized diction system.

DECrad Version 4.0 supports the Health Level Seven (HL7) interface protocol. HL7 is a group of software vendors, users, and consultants working to standardize the data formats and protocol for common transactions. DECrad Version 4.0 also accepts *results entry* transactions, allowing diagnostic reports to be entered from other systems.

The Architecture of Interfaces

An interface implementation consists of three distinct concerns:

- The functions that create or are accomplished by data messages
- The format of the data
- The physical connection between systems

Functions

The most important decision in the design of interfaces, involves the functions that the RIS can accommodate, both sending and receiving. As the number and type of systems that must be connected increases, the flexibility of the RIS interfaces becomes increasingly important.

It became evident, while designing the results reporting feature for DECrad, that the functions within DECrad which trigger the auto-

matic transmission of reports, were only a small subset of the many key *events* which occur during the course of a patient visit. Therefore, rather than create a specific mechanism for sending reports, DE-Crad implemented a generic *trigger event* system. This included an Event Dictionary, which allows the system manager to select which events should cause data messages to be sent, and a queueing mechanism, which "holds" the data until the interface is ready to send it.

The events which define the *typical flow of patient data* in the radiology department can be divided into four major categories, and subdivided into several different *trigger events*. The ability to accept transactions which accomplish the RIS functions implied by these events, as well as sending data based on each of these events, creates a truly open system.

<u>Patient ADT</u>	<u>Order Request</u>	<u>Perform Study</u>	<u>Report Results</u>
Admit	Request	Dispatch	Dictate
Transfer	Approve	Arrive	Transcribe
Discharge	Schedule	Modify	Modify
Register	Cancel	Begin	Approve
Pre-admit	Modify	Complete	Amend
Merge	Depart	Distribute	

The transmission of charge information for radiology exams is not specifically included in this list of events, but is typically associated with the *complete study* or *approve report* triggers. The content, however, must be billing-specific rather than the general event data.

In addition to these specific events, a general purpose query function is necessary. The ability to request information about a patient's history, an exam status, or general management information is useful to a variety of systems.

Other events within the hospital, but outside of radiology, could also generate a message to the RIS. For example, a physician might request a patient's film folder even though the patient is not currently scheduled for a radiology procedure.

Data Formats

To understand the messages that are being sent, a system must know exactly how the data is formatted. Systems must establish rules for transmitting common types of data such as dates, times, and names. Also, there must be a way of identifying each individual item of data in the message. There are three common ways to accomplish this:

Fixed Length

This format requires that each data item occupy a specific number of bytes in a specific position within the message. This is easier for some systems to decode, but has the disadvantage of requiring all systems to modify their software if the length of a data item changes.

Variable Length

This format uses some agreed upon character(s) as markers which delimit the individual data items. Each data item is identified by its relative position in the message. Incremental changes to length or addition of data items can be made without affecting other systems.

Name-Value Pairs

This format uses a data identifier code (name) followed by the actual data (value). As with the variable length records, changes can be made without affecting other systems. It also allows the decoding software to be table-driven, making program maintenance easier.

Physical Connection

The most common method for connecting systems continues to be a point-to-point RS-232 serial line. Many DECrad interface implementations use this method of making the hardware connection. It provides a reasonable, inexpensive solution for the transaction oriented type of interfaces that are necessary. The throughput for this type of "network" is relatively low. But, with multiple lines at speeds of 9600 baud or higher, it should be sufficient for the volume of data generated by even large institutions.

The next evolutionary step toward a more sophisticated network solution is to use a serial line as the end point connection to a local area network (LAN). A terminal server connected to a DECnet network or an interface gateway into a PC LAN creates a good combination of

easy access and high-speed, reliable networking, as well as solving some of the cabling issues related to RS-232 lines.

Because these types of connections do not include the network control to guarantee error-free transmission, it is necessary to create some type of low level protocol that can check for and correct errors. In a more robust network environment, this need is eliminated.

But, creating direct process-to-process communications on a more complex network is somewhat more difficult. DECrad accomplishes this on a DECnet network to other VAX/VMS systems using a psuedo-device, called a *mailbox*, which appears to the application much like a serial port. In a network environment with heterogeneous operating systems, or in mixed network environment using *gateways*, creating the link requires a thorough understanding of both sides of the connection and knowledge of what operating system features are available.

However, as open system standards begin to emerge, it should be possible for the RIS to understand the details of creating these process-to-process connections for the more common networks and operating systems, and then offer those as standard options.

HL7

The basic concepts of transaction oriented ADT, Order Entry, and Results Reporting have been understood for several years, and most healthcare systems have some of these capabilities. Implementing the actual connections between different vendors has usually been a painstaking process. Each application has its own data format, protocol, and functional view. Having two systems agree on and implement an interface is often time consuming and expensive.

In 1987, several software vendors and hospital users met to try and address this problem. From this conference, the HL7 Working Group was formed and has been working to develop a standard, describing this key set of transactions in terms of data formats and protocols. Because the focus of the group has been to create a voluntary, ad hoc standard, it has been able to move very quickly compared with more formal standards efforts.

The goal of HL7 is to create an *application level* standard. The application level is the *seventh layer* of the *International Standards Organization's (ISO) network model for Open Systems Interconnection (OSI)*. However, since the ISO network standards do not yet provide practical support for most applications, the group has also addressed problems dealing with some of the lower levels.

Conceptually, the standard suggests that real-world events create the need for data to flow from one system to another. The *trigger events* cause a message, called an *unsolicited update* to be sent. The standard requires that the receiving system acknowledge the receipt and processing of the message. In some cases, such as an order request, the acknowledgment may in turn contain some data for the original sending system. A slightly different type of message, also defined in HL7, is a *query*. In this case, most of the data flows back to the originating system in the form of a response to the query.

The specification has been designed at three levels to allow a modular design in the interfaces. Interfaces written in this modular fashion can be easily ported from the least robust network environment (RS-232 lines) to a full function ISO/OSI environment.

The top level is the *abstract definition*, which specifies the trigger events, the data fields sent in a message, and the response message. The data is grouped into logical *segments* and the message is composed of a *message header* segment followed by data segments.

The abstract definition includes, for each data item:

- a name for the data
- the maximum length
- the data type
- required or optional
- does it repeat

This level corresponds to layer 7 of the OSI model.

The second level of definition addresses how the data is presented, and corresponds more to layer 6 of the OSI. The *encoding rules* specify variable length data fields, and use a *separator character* to

delineate the individual fields. All data is represented as displayable ASCII characters. The encoding rules also define formats for specific data types such as date, time, name, etc.

The lowest level, appropriately named the Lower Level Protocol (LLP), allows HL7 to be used in network environments that do not provide basic transport reliability. It handles error detection and correction, and is provided as an appendix to the HL7 specification.

Implementing HL7

Most of these concepts were already incorporated into DECrad's existing communications functions. *Trigger events*, a *client-server* model, and most of the basic functions were all in place. Because the original DECrad interface package was designed in a modular fashion, porting the supported functions to the HL7 standard was relatively easy. All the functions (ADT, Order Entry, etc.) were written using *batch screens*, a software tool that mimics the actions of a user data entry screen, handling the application level validation and filing of data. Changes mostly involved writing the Lower Level Protocol and applying the HL7 encoding rules, then presenting the data to the existing batch screens.

The query function was a new concept for DECrad. Results were typically sent to the HIS as the diagnostic reports were approved, i.e. unsolicited updates. This method required the HIS to store large amounts of duplicate data, usually for some preset period of time, or until the patient was discharged. Using the real-time query for results, the HIS or any other system can ask DECrad to send results as an immediate response to their query. These can be sent in a *display* format, where the receiving system does not interpret the data content, but displays the lines of data exactly as they are received. The responsibility of formatting the data is left to the system where the data originated, which is best equipped to handle it. Radiology results can be displayed in a format that closely resembles a radiology report. This function could also be implemented with the RIS as the querying system, so that RIS users can see results from other systems, such as laboratory or pathology.

Other Radiology Systems

In addition to the connections to hospital ADT, orders, and billing systems, DECrad has developed interfaces to two other systems within radiology. Both of these interfaces use some of the existing trigger events developed as part of DECrad's Events Reporting module.

The first was an interface to a digitized dictation system. DECrad produces management reports that allow the progress of diagnostic reports to be tracked and delays in turnaround time to be analyzed. But one of the major milestones in the process, the time that the report was actually dictated, was not captured. As computer based dictation systems replaced tape recording systems, it was possible for the RIS to communicate with those systems, and obtain the missing piece of data. One question was how the dictation system would identify the examination being dictated. Using the *complete exam* trigger, DECrad sends a unique exam identifier (accession number) to the dictation system. The radiologist then inputs that number, in some cases using the barcode label produced by DECrad, to associate the dictation with a specific exam. The dictation becomes a trigger event for the dictation system to send a transaction back to DECrad, containing the dictation date and time.

More recently, DECrad was interfaced to a radiologist's workstation, which uses a speech recognition subsystem, allowing the radiologist to create the ASCII text report from spoken words or phrases. This interface was developed using the HL7 Version 2.0 specification, with extensions to handle free text results (HL7 reserves segment ID codes beginning with "Z" for locally defined messages).

The data flow of the implementation again started with a transaction, triggered by completing an exam, from DECrad to the workstation. Since the HL7 results message includes patient information, this transaction serves as a patient registration, and contains all the necessary exam information. Once the patient and exam are in the workstation database, the report can be dictated, which in turn triggers the transaction to send the report text back to DECrad. DECrad processes the report text and files it along with other data, such as the radiologist's name. If an approval flag is set, then the report goes directly to

an approved ("final") status in DECrad. The workstation, with relatively limited database storage, can delete the patient/exam data as the report is received by DECrad, or when it receives an *approved report* transaction from DECrad (for those reports that may have been dictated outside the workstation).

Other Standards

Two other interface standards are of particular importance to radiology. The ACR-NEMA organization, which has developed a standard for transferring digital images, has established Working Group VIII, whose charter is to develop an application level standard for data exchange between PACS, RIS, and HIS. This group has developed an Entity-Relationship database model for radiology and, from this, created some suggested extensions to the ACR-NEMA imaging standard data dictionary. They are currently working on a functional model for radiology to define the necessary trigger events, and to create a command structure that will handle these events.

The IEEE - MEDIX (Medical Data Interchange) group is working on a general healthcare interface standard. In many ways the group's focus is the same as the HL7 group. But, MEDIX has adhered strictly to the ISO/OSI standards, while progressing in a more deliberate manner than HL7. A convergence between the HL7 and MEDIX group is expected in the next few years.

Conclusion

Much progress has been made in creating interfaces between hospital systems. The effectiveness of sharing data through networking has proven to solve many of the problems created by independent systems. Development of RIS interfaces has historically progressed in reaction to specific needs. But, using past experiences, the standards committees are making the process more proactive, and are attempting to create standards that fulfill future needs.

The creation of application level standards, and the development of open systems networks should greatly decrease the effort and cost of connecting an RIS to other systems.

Teleradiology

BERKOM/RADKOM – A Pilot Project in Berlin to Improve Fast Image Communication between Two or More Hospitals

F. Astinet, M. Langer, J. Hunger, et al

Department of Radiology, UKRV-Charlottenburg,
Free University Berlin, WEST GERMANY

G. Pack and D. Kuritke

Siemens AG, Medicine Technics

B. Scharnberg

Philips Medical Systems Berlin

The BERKOM/RADKOM project

Within the scope of the radiologic communication project (RADKOM), sponsored by the German Bundespost, embedded in the framework of BERKOM (Berlin communication project), PAC-Systems were installed in the two different departments of the Rudolf-Virchow University Clinic at Charlottenburg and Wedding (Berlin), somewhat more than 10 km apart.

Aims of the project are to prove whether a fast ISDN-B test net with 140 MBit/s signal speed is suited for a high quality transfer of radiologic images and if the network is able to establish effective medical teleconferences.

A further objective is to prove how a digital connection between two PAC-systems located in two different radiological clinics helps to increase as well diagnostic accuracy as the effectivity under economical aspects.

Current status

In this moment the PACS-Workstations are connected via an ETHERNET (ACR/NEMA-SPI compatible, 10 MBit/s) with four CT-scanners and two MRI units.

Communication and Image Transfer between both PAC Systems works via an ISDN-B (140 MBit/s) broad band network. Direct consulting between two radiologists will be possible via monitor coupling (4 high-resolution monitors with 1024x1024 matrix) and a videotelephone.

Up to now because of a lacking high capacity gateway (140 MBit/s) between PACS-Computer and ISDN-B, still in status of development until summer 1991, Datatransfer is not fast enough for an instantaneous image transfer during the conference. The actual effective transfer rate amounts about 170 kBit/s. So the transfer of one image with a 512x512 matrix takes about 13 seconds. This situation will be improved by new software programs with accelerated access on the shortterm and longterm archive as well as by implementation of fast gateways, which will communicate bidirectionally between both PACS-computers, without interconnection of the LAN (local area network ETHERNET) with a bidirectional data transfer rate of circa 2 x 64 MBit/s. This leads to an expected acceleration of the data transfer for a factor of about 400. So a command processing, which enables a simultaneous image manipulation and demonstration, followed "live" by the colleague at the other department should be implemented too.

Until a solution of the technical problems for the installation of a digital command processing will be found it is planned to install a temporary arrangement in form of a synchronous cursor operation via video channel on one or two of the monitor screens.

Therefore the conference has to be prepared by background image transfer, which does not interfere neither with the routine-work on the single diagnostic systems (CT and

MR) nor with the postprocessing on the PACS reporting console.

The archiving system includes a winchester-local disc (1 GByte) for shortterm archiving and two digital optical discs (DODs) with a capacity of 4 GByte for a longterm archiving.

After 12 months of experience with PACS to PACS communication it was proved that an effective data transfer rate of only 170 kBit is too slow for a clinical routine work.

A face to face communication in form of an audio-video conference, like it was installed temporarily in our clinic during summer 1989 as well as a command processing, allowing a simultaneous image manipulation, are able to reduce misunderstandings between both conferencing partners and are absolutely necessary for a successful PACS to PACS communication.

The possibility of simultaneous image reporting from different modalities contains not only the advantage of composite analysis of different patients examination with an improved diagnostic accuracy but in addition a composite imaging leads to a composite hardcopy, assembling all the relevant images for the clinical physician. This reduces film numbers and cost in the radiological department.

In fall 1990 image postprocessing will be improved by a PACS-integrated software program with secondary two- and threedimensional reconstructions, regions of interest (ROI) and time-density curves (TDC).

Conclusion

- 1. For an effective PACS to PACS communication, integrated in the routine work of a radiology department, a fast broadband network with a data transfer rate around 100 MBit/s must be available.**
- 2. Beside the fast image transfer an audio-visual communication system is indispensable.**
- 3. A command processing for simultaneous image display and manipulation on all connected systems is desirable.**
- 4. PACS should not be limited on archiving and communication but offer also the possibility of intelligent image post-processing.**
- 5. A complete archiving system should have a possibility of integration of analog data in form of a high resolution digitizer and in addition a documentation system for patients history .**

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Evaluation of Video Image Capture Systems

Alan H. Rowberg

Department of Radiology, University of Washington Medical Center,
Seattle, WA

INTRODUCTION

The clinical needs for image capture fall into the principal areas of teleradiology, archiving, teaching and research. Captured images may be used for quality assurance of imaging devices, for transferring images to a PACS or teleradiology system, or for printing images on a laser film printer. The operational need for a system for transferring images from scanners to other computers may often center around the speed of image transfer, if the capture is to be done simultaneously with image photography, or with scanning with rapid reconstruction and display. Another critical item is ease of use, which includes a method for ensuring reliability of demographic information. Finally, and most important, there must be the appropriate level of fidelity of the images, for the window width and window level being used.

In the future we will have digital connections from all our newer digital modalities. This will be in the future, however, because of the slow adoption of the ACR/NEMA standard. Perhaps a bigger factor is the large number of scanners currently installed for which digital interfaces will never be available. Thus, for some imaging devices, video image capture will always be the only interface method available.

METHODS AND MATERIALS

Evaluation procedure

Five commercially available image capture systems were evaluated: Philips/AT&T CommView[®]System, Adaptive Video, Advanced Video Products, Epix, and Images-on-Call[™]. CommView is a registered trademark of AT&T and Images-on-Call is a trademark of Devices and Services Co.

The evaluations were done using a single CT9800 scanner. A series of digital images were programmed on the scanner and used as phantoms for the evaluation.

The technique used to make these images available for capture is one which can be used with almost all imaging devices. The images are stored in the form of a routine patient examination on the archive media which are standard on the imaging computers. The method requires only the ability to read and write the archive media on any computer which can be programmed. Ideally, the scanner manufacturer would make appropriate images available in archive format.

These images have been designed to be simple in structure, and can be easily programmed. In addition, they are available on tape and floppy disk in a variety of formats. They are easily understood on the display at the scanner, so the user can verify that they have been displayed correctly. After images are captured, they are displayed on the standard display on the receiving system, either a teleradiology system or a PACS display workstation.

The scanner was connected to the image capture devices with a thirty foot double-shielded 75 ohm coaxial cable. One device came with a five-foot video cable with four coaxial connectors, which was used instead. The resulting digital images were transferred to a single computer and analyzed there.

Test images used

These evaluations were done with a series of digital images, displayed on the CT9800, using the standard display program. All of these analyses were done using a similar procedure. The images were either programmed on a PC, or on the CT scanner itself. Each image was then displayed on the scanner with full resolution and accuracy, and the window width and window level controls set appropriately. The image was then captured by the image capture device and stored digitally. Images were transferred to the another PC and the image converted (without error) to another data format which is used for display and analysis.

SMPTE Test Pattern -- This image was probably originally developed in digital format by Joel Gray at the Mayo Clinic, and given to us by Jerry Gaskill, at George Washington University, who got it from the Center for Devices and Radiological Health.

256 shades of gray -- This image presents all 256 shades of gray with equal areas (except for black, which predominates). The shades of gray are arranged in 256 contiguous areas which are each small rectangles, wider than they are tall.

Eight Bars -- This image contains eight vertical bars that cover the whole image vertically. Each bar is 512 pixels tall and 64 pixels wide. The darker bars are at the left side of the image and the lighter bars are at the right side of the image, being separated in brightness by one display unit each.

Uniform field -- This image is a flat field with all pixels the same value. In use, the window level control is used to set the image brightness to a certain value, usually not 128, because of the nonlinearities which may occur at this point.

Horizontal 256 ramp -- This image contains a set of vertical lines, progressively brighter as they are closer to the right-hand side of the screen. Each brightness is repeated once, so the 256 brightness levels are spread out evenly across the screen.

Vertical 256 ramp -- A ramp which changes in brightness in the vertical direction.

Alternating BW with stripes -- Alternating black and white vertical lines, each one pixel wide. Two vertical stripes, each 10 pixels wide, are used for calibration of the full black and the full white values.

Alternating BBWW with stripes -- The same alternating pattern except each vertical line is two pixels wide.

Black and white half-screens -- These images are all black on one-half of the screen (i.e., left or top), and all white on the other half, and may be used to calculate MTF.

Clinical CT scans -- Several CT scans were selected to show subtle features.

RESULTS

Philips/AT&T CommView

The most exhaustive testing was done on this system, since it is an integral part of the PACS system installed at the University Medical Center. The image capture system serves three scanners and is located in a computer room remote from all the scanners, and about 400 feet from the CT9800. It was thus tested with video cables much longer than the other systems, with a commensurate degradation in performance.

The 256 shade of gray image was captured and its histogram displayed. After a spike for the black portions of the image, this histogram should be precisely flat, with each shade of gray having exactly 576 pixels in it. Instead, the darkest portion of the image varies considerably, and the lightest half of the image has an oscillation with a period of seven shades of gray.

The sawtooth appearance of the histogram was caused by the interaction of the physical arrangement of the grayscale steps, the limitation in dynamic range, and a vertical shading in captured images caused by a hum filter.

More recently, we have received an updated version of the frame grabber card, which is now a pre-production prototype. It contains a daughter board which has faster video circuitry and a more sophisticated method of synchronizing with the imaging modality video source. It has redesigned circuitry with a faster video amplifier, a DC offset voltage adjustment, and better ability to synchronize with the scanner video signal. A new video preamplifier with a wider bandwidth was also installed. In addition, a higher quality video cable was installed between our CT scanner and the video frame grabber (Belden 8281) and the video distribution amplifier was removed and replaced with a much more sophisticated amplifier developed by AT&T specifically for this application. It allows the service engineer to adjust the characteristics of the amplifier to match it to the particular length of coaxial cable installed, compensating for high frequency losses which occur in the cable.

We also installed a fiber optic link with coupling amplifiers which convert the video signal on coax to a signal compatible with the fiber optic cable, and convert it back again at the receiving end (Merit, Inc.).

The combination of the new frame grabber circuitry and the wider bandwidth video cable/amplifier combination greatly improved the capability of the system. The 60 Hertz hum filter was no longer required, so the captured images have very little vertical shading. There is still a small amount of noise, but the horizontal banding previously seen in the images is not visible unless images are viewed at extremely narrow windows. The system now synchronizes correctly with alternating black and white lines, with slight shifts in phase being seen as small variations in the density of the lines, causing horizontal streaks. When the viewing window is narrowed greatly, this variation is easily seen at the upper and lower ranges of the gray level value scales.

Alphanumeric characters displayed over clinical images are now captured perfectly at all settings of window width and window level on the CT scanner. Although a small amount of blurring at the edges of the characters can be seen at extremely narrow window settings, this does not interfere with a computer algorithm for the automatic recognition of characters. Therefore, using this improved circuitry and cabling, it is now possible to automatically read the name of the patient, date of the exam, and other demographic information directly from the image at the receiving end of the image capture. This may be used to supplement information typed by the operator, or to verify that the information typed by the operator is correct, thus preventing incorrect patient identification.

As expected, the results using the fiber optic link were even better than those over coaxial cable. The phase errors seen in the alternating black and white line phantom were nearly totally eliminated, so that the noise at the extremes of the CT number range was lowered to about 10 grayscale units.

It now appears that coaxial cable will be adequate to support all clinical and most research uses of images captured by the video frame grab techniques over short to intermediate cable lengths, 400 feet at our installation. In the event that longer cable lengths are necessary, transmission of the video over fiber optic is a viable alternative.

Adaptive Video

The Adaptive Video system is a standalone device, not requiring an external computer. It has an attached hand-held controller, and is designed as an image interface, commonly used to drive another device, such as a laser image printer. It synchronized perfectly with the CT scanner pixels at factory settings, with a slight limitation in slew rate, probably because the slower of the video input ports was being used. Its synchronization was stable across the image. This resulted in accurate grayscale rendition and perfectly sharp text. The text was so reliable than an automatic character recognition program to read the patient name and ID information from the image and store it in a database was easily developed.

Advanced Video Products

The Advanced Video Products (AVP) system evaluated is a component of their DICAP 1280 teleradiology system. The image capture is performed by a single card in a 286-class computer. The system would synchronize with the pixels when the cover of the computer was removed and a potentiometer adjusted. This adjustment was stable within clinical tolerances, although some drift could be detected with the alternating line image.

EPIX

While EPIX, Inc. manufactures many different models of video image capture cards, the one evaluated was a SILICON VIDEO MUX with 1 megabyte of image memory and a 30 MHz maximum clock rate. It is a single board which fits into any computer with a PC/AT bus. It was configured with four coaxial connections to the CT scanner, including video, pixel clock, horizontal drive, and vertical drive. The SVIP software provided allows the user to configure the device for the video format of the CT scanner.

As expected with the pixel clock connection, the image capture was reliably synchronized with the pixels in the CT scanner image. There was a minor limitation in the slew rate of the multiplexor on the card, and the device could not switch completely from black to white in a single pixel.

Images-on-Call

The Images-on-Call system, from GE Medical Systems, is based on a small stand-alone image capture box, approximately 2 x 8 x 10 inches, which can be easily located near the scanner video source, with a remote hand-held controller with LCD display and alphanumeric keypad. In normal use, it is connected to a modem and used for teleradiology, but in this evaluation it was connected to a PC using an RS-232 cable so images could be captured to disk locally.

Of the systems tested, it was unique in its ease of use. It is designed to automatically adapt to the video format being used, and so requires no manual adjustments to match the particular scanner. In fact, the device could be moved from an NTSC video source to a CT9800 without even telling the device that a change was being made. It would automatically sense the video characteristics of the CT scanner, and adjust its matrix size, synchronization, and acquisition voltage levels to match the CT image.

Despite its small physical size, the performance of the unit was impressive. It had a low noise, with a range of 2 grayscale values and yet was fast in switching from one video level to another. It never drifted out of calibration, since it adapts to the video each time it is used. It uses a matrix size of 500 x 524 for CT9800 video, and a grayscale range of 240 so some of the image phantom tests could not be run. This limitation causes slight blurring at the edges of some alphanumeric characters, but does not interfere with the device's stated use in teleradiology.

CONCLUSIONS

The factors determining the quality of captured images predictably include short lengths of coaxial cables, high quality cable with excellent shielding and low loss, which gives the cable wide bandwidth. The video capture system must not effect any other imaging component, such as displays or image hardcopy printers. Configurations which did not require the use of video amplifiers tended to give better image quality. Loose or noisy cables proved to be a frequent source of problems.

There are many reasons for taking the trouble to align the pixels as captured precisely with the pixels as displayed. First, the best grayscale accuracy can be obtained only with proper alignment and digitization. It may be possible to perform quantitative analysis on properly captured images. The alphanumerics will be crisp only if the alignment is correct and reliable across the field of the scan. This makes them easily readable and fully professional in appearance. It is also possible to apply optical character recognition techniques on the captured images for validation of demographic information.

Although there are many benefits to using video image capture, there are also some drawbacks. Images are captured in 8-bit format, so one must set the window width controls to trade resolution for range, and several captures may be required per image. The transfer of ASCII demographics is not automatic, and there must be some manual intervention after the viewing controls have been set. The duration of capture may be annoyingly long, and any misadjustment of the equipment may lead to glaring pixel edge effects, such as in the image annotation.

The advantages of video image capture begin with the convenience and availability of interfaces for a large number of different scanners, and go on to include capturing images which are pre-windowed and ready for display. The interface method can be very fast, in terms of the scanner time required to accomplish the capture. Also, the capture system may offer multiple outputs, and multiple capture systems may be installed, to get around the limitation of a single digital output port, such as ACR/NEMA, which could be used to drive a laser film printer, or a PACS system, or a teleradiology system, but probably only one at a time.

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All manufacturers of the image capture devices evaluated cooperated with this work by loaning the hardware and software required, providing technical support by telephone, and some by providing onsite technical or engineering support. Bioscan loaned image display equipment and analysis software. Americable and Belden provided the special high-quality coax. All this assistance is gratefully acknowledged.

Quality of Remotely Transmitted Images

Charlotte A. Hammond, Robert R. Hattery, Bernard F. King, et al,
Department of Diagnostic Radiology, Mayo Clinic and Foundation,
Rochester, MN

Introduction

Telecommunications systems and networks for image transmission have been used over the past four years within the Mayo Clinic to support clinical practice, research, education, and administration. Some examples of these systems include interactive real-time video for transmission of imaging examinations recorded on x-ray film, transmission of real-time ultrasound procedures, transmission of patient examinations in a consultative practice of medicine; console-to-console links between CT and MR systems; and, compressed digital image transmission of a variety of examinations. The networks include coaxial cable for local area networks, fiber optic links for intermediate distances, and a KU band satellite transmission network for long distance communication between Mayo Clinic in Rochester, Minnesota; Jacksonville, Florida; and Scottsdale, Arizona. In addition, the phone lines are used for transmission of compressed digital images between and on all three campuses.

The utilization of image transmission in Diagnostic Radiology has increased significantly with expanded imaging technology.^{1,2,3} This study was performed to validate image quality and determine relative accuracy of different transmission modalities within the Mayo Clinic Telecommunications System.

Methods and Materials

Signal-to-noise, resolution, and image quality were compared using Ektascan-phone line [Kodak Ektascan Image Transmission System; T1/R1 Software, Version 1.30;

Rochester, NY] (compressed digital), Proview-fiber optic, and Proview-satellite [General Electric Proview Plus; Milwaukee, WI] (real-time interactive video) transmission of intravenous urograms.

Signal-to-noise measurements were made utilizing the "spatially-adjacent noise matching" technique. The video source was connected to a Tektronix Model 1430 Noise Measurement Set. The feed-through output of the 1430 was then connected to a Tektronix Model 1481R waveform monitor. Precision, weighted noise generated by the 1430 was injected into the video signal and matched to the noise level of the source device. This was typically done on line 21 of the video signal.

The resolution of the systems was evaluated using two different test patterns. The first was a conventional monochrome high contrast reflectance pattern calibrated in TV lines. The second pattern was a radiograph of copper mesh which is conventionally used for evaluation of fluoroscopic systems in diagnostic imaging. All transmission systems were evaluated using monochromatic monitors.

Intravenous urograms were selected to demonstrate image quality and accuracy of detection of various grades of tubular ectasia.⁴ Collecting duct dilatation was chosen for study because of the spectrum of involvement from minimal to severe with the thought that differentiating minimal involvement from normal would test the limits of the different transmission systems. Sixty normal and 140 abnormal urograms were graded, randomized, and reviewed independently by three observers (RRH, BFK, BW). Digitalized images transmitted via phone line and real-time video images transmitted via fiber optic and satellite systems were utilized for the study. Each observer was required to indicate grade of tubular ectasia, confidence level, and quality of image.

Grading of the cases was determined by degree of dilatation of collecting ducts with Grade 0 being normal, Grade 1 mild dilatation, Grade 2 moderate, Grade 3 marked, and Grade 4 severe. A total of 200 representative films were selected and graded. The cases included 60 normals, 60 Grade 1, 56 Grade 2, 16 Grade 3, and 8 Grade 4. The cases were then randomized to one of four groups labeled W, X, Y, or Z. Each group contained 50 cases composed of 15 normals, 15

Grade 1, 14 Grade 2, 4 Grade 3, and 2 Grade 4. Reviewers were unaware of the relative number of each grade number in each group.

The experiment was designed so that three uroradiologists each reviewed two groups of film on every modality for a total of 100 cases. One group of films was seen on every modality by every reviewer (Group W) while one group of films was seen by each observer only once (Group X, Y, Z).

METHOD OF TRANSMISSION

<u>Reviewer</u>	<u>Ektascan Phone Line</u>	<u>Proview Satellite</u>	<u>Proview Fiber Optic</u>
1	XW	YW	ZW
2	ZW	XW	YW
3	YW	ZW	XW

This arrangement allowed us to evaluate consistency on each reviewers part, consistency among the reviewers, and variability on different transmission systems. For each case the reviewer evaluated Grade 0 to 4, confidence level as uncertain or certain, and quality of image as poor, adequate, very good, or excellent. The reviewer could optimize the image by whatever options were available on each piece of equipment. No time limit was imposed. The pre-graded standard cases were available for review during evaluation.

Discussion

A signal-to-noise ratio of 60 db was considered an excellent image with the noise undetectable to the human eye. The Proview system was determined to have a signal-to-noise ratio of 47 db. The fiber optic link did not add significant noise. Non-encoded satellite transmission was excellent at 58 db. With the necessity of encoding or scrambling the image, additional noise was generated decreasing the signal-to-noise ratio to 48 db. The signal-to-noise ratio of the Ektascan system was not considered reliable because of the low resolution which produced blurring. The blurring of an image results in blending each image point with its surrounding area. The effect was to smooth out noise

and make it less visible.

The resolution of the Proview imaging system for the high contrast (reflectance) pattern was determined to be 500 TV lines. Some loss of resolution was noted when the video signal was transmitted over the satellite decreasing the resolution to 450 TV lines. The resolution of the Ektascan system on the high contrast pattern was 250 TV lines. However, the Ektascan resolution using the low contrast pattern was approximately equal to the Proview system at 24-30 lines per inch. This result might be anticipated since it is necessary to filter the analogue video signal prior to digitization. The filtration will primarily affect the high frequency components. The low contrast resolution pattern will be affected most by noise. In fact, filtering the analogue video signal prior to digitization will decrease the noise in the signal providing better low contrast resolution.

Measurement of signal-to-noise and resolution provided an objective evaluation of the different systems. Whether there was any subjective difference in the systems was the next question to be addressed. The grade assigned by each reviewer was compared to the pre-experiment assigned grade and tabulated for each reviewer on each method of transmission. A trend in the number of correct responses was noted when comparing the systems. The Proview-fiber optic system had the most correct responses. There was, however, no statistically significant difference in detection of normal versus abnormal or in determination of the severity of dilatation within one grade. Despite disagreement or variability in grading amongst the observers, in 98% of the cases they agreed within one grade of the pre-assigned grade and in 87% of the cases the correct diagnosis of abnormal versus normal was made. Individual performance on each method of transmission was also considered. While two reviewers were more accurate on the Proview systems, one reviewer had the opposite results. Combining the results, no statistically significant differences were identified.

The kappa statistic for each method of transmission was calculated. The kappa statistic is similar to the correlation coefficient and measures the ability of the reviewers to agree with each other. Values less than .4 show no real agreement, values between .4 and .75 show

good agreement, and values greater than .75 show excellent agreement. The kappa values obtained range from .44 to .55.

KAPPA VALUES

	<u>W</u>	<u>X,Y,Z</u>
Ektascan-phone line	0.44 (0.33-0.55)	0.45 (0.35-0.56)
Proview-satellite	0.46 (0.36-0.57)	0.55 (0.45-0.65)
Proview-fiber optic	0.54 (0.43-0.64)	0.50 (0.39-0.60)

These values are at the low end of the range and overlap each other. These values indicate that there was more variability between reviewers than there was between methods of transmission.

Reviewers also evaluated quality of images and rated them as poor, adequate, very good, or excellent. The Ektascan produced more images rated poor and fewer were perceived as excellent than did the Proview systems. There was virtually no difference between the Proview-fiber optic and Proview-satellite system. There was no correlation between the perceived quality of the images and the percent correct for any of the modalities. Similar results were obtained for all groups of film evaluated. The confidence of the reviewers varied directly with the perceived quality of image for all methods of transmission. There was, however, no significant difference in accuracy.

Conclusion

There was no significant difference in accuracy of interpretation using transmission of data via Ektascan-phone line, Proview-fiber optic or Proview-satellite. There was more variability between reviewers than between methods of transmission. The reviewers were more confident of their assignment of grade when the quality was perceived as high. Although there were general trends showing the video images to be better than compressed digital images, the results did not reach statistical significance. The reviewers all expressed a subjective preference for the images generated on Proview and transmitted in a real-time interactive video mode.

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ADA Tele – Radiography Workstation

Fupei Hu, Yao Zhang, Lulin Hua, et al

ADA R&D Group, ADA Digital Systems Inc., Beltsville, MD

Huchen Xie

Radiation Oncology Branch, National Cancer Institute, NIH,
Bethesda, MD

Tianpei Hu

Institute of Rehabilitation Engineering, Shanghai Jiao Tong University,
Shanghai, PEOPLE'S REPUBLIC OF CHINA

Abstract

A powerful, low-cost, 386 based image workstation - Tele-Radiography system TR200 with multi-functional capabilities has been developed by ADA Digital Systems, Inc. for high performance medical image applications. This workstation provides an integrated image manipulating environment that offers a unique combination of capabilities to capture, process, store, retrieve, print, and distribute medical images through telephone lines. Featuring a versatile packaging design, the TR200 can be configured as a dual medical image viewing, an image communication, an image database management, and an image desktop publishing workstation. The TR200 workstation provides a video camera and a light box to capture images from X-ray films. A powerful image processing software package provides the tools for image enhancement, image measurement, edge detection, image geometric transformation, etc. The dual monitor display makes it convenient for doctors to compare two X-ray images. Using ADA image communication software package, images can be transmitted from one hospital to another via modems and telephone lines. The software makes it possible for doctors to discuss the cases of patients when one workstation displays the X-ray image of a patient while another workstation at a remote site displays the same image by getting it through telephone lines. The doctors from these two hospital can work simultaneously to deal with the same image. They can enhance the image, draw

polygons and write text on the image using a remote image processing technique, i.e. one station can be the master which controls the slave - the remote station. All the operations of the image processing will be simultaneously performed on the two workstations. The sophisticated image compression, encoding, and decoding algorithms of ADA ensure the high speed image data transmission and receiving. The relational image database of ADA can store and retrieve not only the text information, but also the image information of patients. Images can be printed out on regular papers by a high resolution laser beam printer to get clear hard copies. The modular design and user friendly screen menu interface of TR200 affords the system flexible and easy for use. Simplified operations are also provided for daily operation. In an one key operation, image capture and enhancement are performed automatically. Bulk images can be selected and sent out at night by a sophisticated image communication package without the people on duty. Two ADA TR200 Tele-Radiography workstations have been successfully installed in the Johns Hopkins Hospital at Baltimore, MD and the Chambersburg Hospital at Chambersburg, PA respectively.

INTRODUCTION

In medical imaging applications, an integrated system which facilitates those functions as capturing, processing, communication, etc. will be widely used in the field of radiation therapy. Doctors can capture pictures from films into computer. The digital images are enhanced by various algorithms to highlight certain interested organs or analysis some features. Measurements and statistical results are easily obtained. It is often the case that doctors in local hospitals want to link to medical research center so they can benefit from the extensive knowledge of academic institutes. Through telephone lines, digital images can be

transmitted from station to station. Doctors can discuss patient's cases on line where displaying and processing the same images on computer monitor screens.

ADA Digital Systems, Inc. thus developed a powerful, low cost, 386 based medical imaging workstation Tele-Radiography 200. The system includes a 386 Personal Computer, a light box, a camera, an image digitizer and processor, a system monitor and an image monitor, a mouse, and a modem. First, the film on the light box is digitized into computer. It is automatically enhanced based on its histogram. A pair of images is grouped together displaying on the two screens for comparison. Normally one comes from simulator, the other is portal film. Bulks of images can be prepared and sent to another station through telephone lines at the night. So doctors in both stations can preview those images before discussion on line. During the conference, all the operations are in master-slave mode, that is to say, the master station totally controls the slave. Of cause, master and slave can be easily exchanged.

In the following sections, we will give a brief description of the system TR200.

SYSTEM DESIGN

For an application system, it should be very easy to use and flexible enough to add in more functions according to user's needs. Although it is easy to add in functions, the command driven operation is not good for doctors to use it. Doctors almost always found they are confused by the strange command names and lots of arguments. So we designed a menu driven, modular structured interface.

In the menu, a function is selected by using arrow keys to go to the function item. Then it is evoked by hit the Enter key. We group those

items by their usage. Due to the modular nature, it is fairly easy to have a new function added into it. Actually, we have more than 200 separate imaging modules, they can be tailored to most specific needs.

In the development of Tele-Radiography System, we cooperative with doctors in hospitals and try to do things according the way doctors used to. In medical imaging, we find that the cooperation between doctors and computer engineers is very important. Several functions in the system are written to meet the specific needs of doctors.

FUNCTIONS DESCRIPTION

1. Image Capturing

The system grabs one frame in real time - within 1/30 second. Live image is displayed on the screen while it is digitized into the frame store. The size of the digital image is 512 by 480 pixels, one pixel has 8 bits or 256 grayscales. To reduce the noise, several images are averaged in the frame store. The digitized images can be stored in hard disk for later retrieval.

2. Image Processing and Editing

By using image processor, the quality of X-ray images can be greatly improved. The technique we use is called interactive histogram transformation.

Those traditional techniques such as edge detection, high pass or low pass filtering, sharpening, etc. are also provided. When two images are displayed on the screens, texts and polylines can be drawn on the images. Measurements of length or area on interesting object can be also got while doing calibration before measure.

A detailed list of image processing and editing functions is shown below:

- Image Display
- Scroll, Pan and Zoom
- Rotation or Reversing
- Show Pixel Value
- Drawing Polyline
- Writing Text
- Calibration and Measurement
- Histogram Enhancement
- Image Sharpening
- Edge Detection
- Mean Filtering
- Negative Picture
- Vertical or Horizontal Profile
- Addition or Substraction
- etc.

3. Image Transmitting

It is very convenient to prepare all the films before conference and send them at the night. When images are captured and stored in hard disk, doctors can work out which pairs will be showing and select the images want to be sent. After that, ask doctor at the other end turn on the machine and enter the receiving mode. If everything is OK, set the time to transmit and leave it there. When the time comes, the sender automatically dial the phone. If connected, send all the images selected. Then hang up the phone and give the message about the transmission.

During transmission, if there is anything wrong, the system will send that part again. Of cause, it only tries several times in case of sever errors occurring on the line. This will prevent from unnecessary connection for a long time.

Even though we use a 9600 baud modem for transmission, it will still take about 5 minutes to send one whole picture. However we developed a compression utility to reduce the size of the transfer data. For most X-ray films, the compression ratio is around 1/3. That is to say,

the transmitting time is just about 1 1/2 minutes for one image.

4. Remote Imaging Control

In terms of remote imaging control, we mean to transmit, manipulate, and edit images on the screens interactively where two stations is linked together by ordinary telephone line and they are doing exactly the same thing. So doctors in deferent hospitals can sit in front of their own computer, look at the screens, control the process, and discuss about patient's cases.

In the system, communication is implemented in master-slave mode. Master has the total control of the slave. Master can draw polylines, write text, or do image processing where the slave behaves the same as the master. For example, after master has the polylines drawn on the screen, the slave has the same polylines appeared on its screen.

For efficiently and correctly transmitting data and command over ordinary phone line, we developed a packet communication protocol. A packet contains all the information about transmitting sequence, command, data, and check value. When it is received by the other end, after checking the received bits, the command is executed at the same time with the sender.

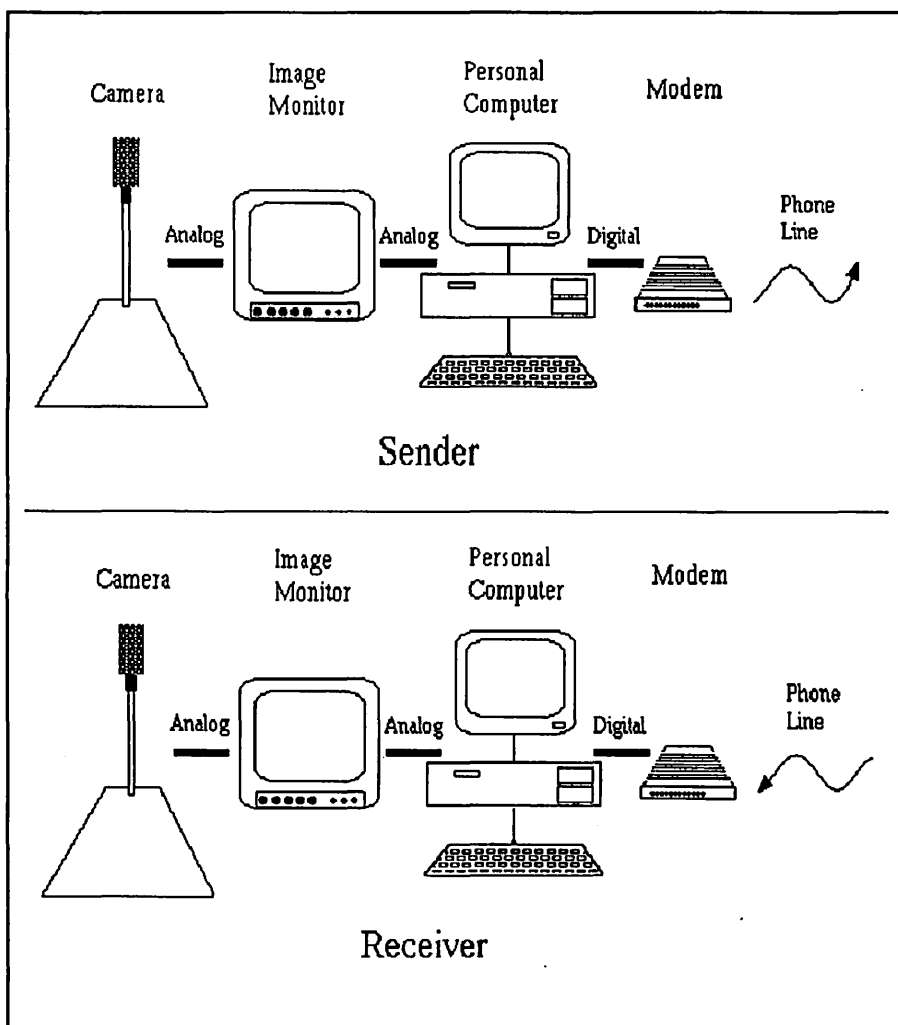
5. Image Management and Printing

Sometimes, it is useful to store the images and related patient data in a database, we provide the option to do the image management and organization functions. Also the images - original or processed - can print out by laser printer.

CONCLUSIONS

Now, the ADA Tele-Radiography System TR200 is put

in use at the Johns Hopkins Hospital at Baltimore and Chambersburg Hospital in Pennsylvania. Because it integrates imaging, communication, printing, etc. into one complete system, it is an ideal computer assistant for radiology. Doctors found it very easy to use and powerful. The cooperative development process with doctors is a good way to implement such kind of specific application system. Now we are work on the new function to capture images directly from X-ray beam. So we do not need to always take pictures on films.



Teleradiology for Remote Evaluation of CT Scans at a Rural Hospital

Jeffrey L. Chenoweth and Carroll R. Markivee

Department of Radiology, Saint Louis University School of Medicine
and John Cochran Veterans Affairs Medical Center, St. Louis, MO

INTRODUCTION

Patients who live in remote or rural locations have always had difficulty in obtaining access to modern high quality medical care. Many are fortunate to have even basic services available. Expensive high technology imaging procedures such as computed tomography (CT) and magnetic resonance imaging (MRI) have revolutionized the practice of medicine yet remain unavailable due to inherent high costs and low volumes in such rural areas. In an effort to meet this need mobile equipment on trailers towed by trucks has been developed which would make the unit available on a periodic basis. Unfortunately due to distances involved and low volumes of exams it often is not possible to have a trained radiologist on site for immediate evaluation of the images obtained. Even when a radiologist is available, he or she may not be trained in the newer imaging modalities and would benefit from consultation with subspecialists in these areas.

Teleradiology systems have been proposed to help solve this problem. Teleradiology is the evaluation of radiologic images transmitted from a distant site. We report on a pilot program to evaluate the feasibility of providing remote interpretation of CT scans using a commercially available microcomputer-based image transmission system (ITS).

METHODS

Over a four month period 49 CT scans were performed on 41 patients at a rural Veterans Affairs hospital at Marion, Illinois and transmitted for evaluation at a tertiary care Veterans Affairs Medical Center in St. Louis, Missouri, a distance of 120 miles.

The CT scans were performed on a CT9000 (General Electric, Milwaukee, WI) mounted on a truck which was available for one or two afternoons a week. The examinations performed included 19 head, 16 abdomen, 9 pelvis, and 5 chest scans. The studies were imaged as usual with a 12 on 1 format onto a 14x17 in. film and subsequently digitized.

The ITS utilized was the commercially available Ektascan (Kodak, Rochester, NY). The filmed CT images are placed on a lightbox above which is mounted a vidicon camera with a macro zoom lens. The camera is interfaced to an IBM PC AT microcomputer with a proprietary frame-grabber board. Up to 85 images can be stored on the 20 MB hard disk. The images are acquired as a 512x512 matrix, but displayed as a 512x480 matrix on the separate control/display monitor, with 256 gray levels. The internal 9600 baud modem transmitted the data over ordinary telephone lines to the similar receiving unit. The system utilizes a 2:1 data compression method to allow image reconstruction without data loss. The images were stored on the hard disk of the receive module for evaluation by a staff radiologist who would phone the results to the referring hospital. Several days later the filmed archival images were received for final diagnosis.

RESULTS

The ITS is capable of displaying an image of a standard 14x17 in. film on a 512x480 matrix. Preliminary experiments showed that such images were not adequate for evaluation of the typical 12 on 1 CT format due to loss

of detail. The vidicon camera is equipped with a macro zoom lens capable of optical magnification of selected portions of the filmed images. This results in an effective increase in matrix size and improved image quality (1). This capability was used to transmit each CT image separately.

A total of 49 examinations were evaluated, including both normal and abnormal studies (Table 1). The head CT scans included cases of tumor, infarct, and atrophy. The chest scans included lung tumors and aortic aneurysm. The abdomen and pelvis scans included cases of simple and complex renal cysts, liver cysts, ascites, aortic aneurysms, and tumors of the kidney, liver, prostate, and bladder.

Table 1. CT Findings in 41 Patients

	head	chest	abdomen	pelvis
normal CT	5	0	2	5
abnormal CT	14	5	14	4
.....				
infarct	4			
atrophy	8			
mass / tumor	2	4	4	4
cyst			8	
ascites			2	
aneurysm		1	3	
other	1		5	

Note: several abnormal scans had more than one pathology.

In this series there were no major disagreements between interpretations from the transmitted and hard copy images; the site of pathology was correctly determined in all. As anticipated, the confidence level of the radiologists was considerably higher with the film images than with the digitized images. In particular, distinction of fine density differences (such as a simple cyst versus abscess) or subtle changes in edge characteristics (such as simple versus complex

cyst) were often difficult to evaluate on the monitor. Transmitting images with region of interest density measurements made on the original scans helped to some degree in this regard. The transmitted images nonetheless required more careful evaluation than the film images and often needed manipulation with the display controls.

The time element became an important factor in the system. Transmission time for one image is approximately one minute at 9600 baud. A standard 22 image head CT would thus take about 22 minutes to send, a standard chest CT could take 50 minutes or more. The software can be set for unattended transmission and reception.

Another time factor of critical importance is the time required for the radiologist to evaluate the transmitted images. Only one image is available at a time. Although any image can be recalled from the hard disk in a few seconds, it can be tedious to review a whole set of images, particularly as many required further manipulation with the window/level, zoom, or histogram equalization controls. Also, radiologists are used to quickly scanning a film to construct a mental 3D spatial relationship. This is considerably more difficult when all the images are not visible at once. In addition, more care and time is needed to compensate for the relatively decreased detail available on the ITS.

DISCUSSION

Teleradiology systems have been available for over three decades (2). They have been used for transmission of standard radiographs obtained in hospitals, emergency rooms, and clinics (3-6). A natural extension of this developmental process is the remote transmission of examinations such as CT and MRI scans. Many of the previously reported ITS are impractical due to expensive or one of a

kind equipment configurations. The development of microcomputer-based ITS have now resulted in commercially available units at a reasonable cost. The simultaneous development of mobile CT and MRI scanners has made it possible to offer these services to patients in remote or rural locations.

This pilot program was designed to evaluate whether such a service was feasible from a diagnostic and economic standpoint. We were encouraged by the agreement in interpretation of the transmitted and filmed images. Nonetheless, further work is required to evaluate the sensitivity and specificity of the ITS in a wider range of pathology, and in particular in the evaluation of subtle alterations in tissue density. Such differences are essential to the radiologist's confidence in image evaluation. Since the digitized images are derived from an analog filmed image, there is of necessity some loss of diagnostic information, as has been shown in transmission experiments involving plain radiographs (4,5,7-9). Direct transmission of the original CT data might overcome this limitation, but would require dedicated specialized interface equipment.

Several methods of data transmission have been employed in the past, including direct coaxial cable, microwave, and satellite communication (2,3,10). Telephonic links as used in our study have the advantage of low cost and nearly universal availability. The prime drawback to this method is the time required to transmit the large volume of data required for CT scans -- up to an hour at 9600 baud for a standard chest CT. Data compression algorithms can cut the time requirements, but at the cost of image quality. In the future, integrated services digital network (ISDN), a developing telecommunications data standard, offers the promise of much greater data rates while preserving compatibility with current

telephone wiring (11).

The second goal of our project was to evaluate potential for improved patient care via this system. Previously patients had to be transported 120 miles to a tertiary care center to obtain a CT scan. Such travel was difficult for the sick inpatient. It was also a burden on the outpatient who had to miss work. Both groups had to be hospitalized overnight before the return trip, further increasing costs. The immediate evaluation of the images allowed more timely patient care. The number of abnormal exams in our series demonstrates the need for such a service.

We have been encouraged by these preliminary results and plan to continue further evaluation, particularly in regard to sensitivity and specificity of subtle lesions.

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Comparison of Frame Grabber Boards for Medical Imaging

Peter D. Esser and Lawrence M. Buxt

College of Physicians and Surgeons,
Columbia University, New York, NY

Introduction

Frame grabbers are frequently used in medical imaging systems to convert analog video signals into a digital matrix for viewing. The applications using this technology include tele-radiology, ultrasound, nuclear medicine, and teaching systems. While the quality of images captured by frame grabbers is generally less than those generated by laser scanners, the systems are considerably less expensive and are believed to be have adequate resolution and gray scale range for many applications.

As part of a research project to digitize cardiac angiographic images from 35 mm cine film, we needed to develop an inexpensive system to acquire and store these images for computer analysis. The Macintosh II computer (Apple Computer) was chosen as the developmental platform. Since there were a wide variety of high-resolution, commercial, 8-bit frame-grabber boards available for the Macintosh system (as well as for other small computers) with similar specifications (640 x 480 frames from RS170 video signals) and little information in the literature on their suitability to medical imaging systems [1-3], we have made a comparison of four state-of-the-art boards suitable for our application. All board were capable of digitizing and displaying an entire image in real time (1/30 sec) for processing on a personal computer.

Materials And Methods

Frame grabber boards and their accompanying software packages were obtained from the following manufactures:

A) Quick Capture Board (DT2255-60Hz), Data Translation (Marlboro, MA).

B) Image Grabber Board, Neotech Group Limited, Camberley, Surrey, England.

C) NuVista Board with 1 MB internal memory and Truevision NTSC VIDI/O Box (encoder/decoder), Truevision, Inc., Indianapolis, Indiana.

D) Video Image 1000, Scion Image Systems, Walkersville, Maryland.

The Scion board did not contain an internal buffer memory; it used the host computer's NuBus to store images directly in the computer's memory. This board was unique in that it could display true live time video images on the Macintosh screen (with as small truncation in image size). Boards A, B, and C captured full size images: boards A, B displayed images close to real time on any appropriate monitor connected to the computer; board C connected directly to the Apple 13 inch monitor and was not able to display live images during capture. Each board occupied one expansion slot on a Macintosh II computer (8MB memory, E Machine TX color monitor and Apple 13 inch color monitor, 8 bit video cards). Input video signals for the boards were generated from 3 sources: 1) PDP-11 Nuclear Medicine Imaging System (PCS-512, Picker International), 2) TSG-51 Video Pattern Generator (General Electric) with a checker board test pattern with gray scale ramps, and 3) a custom cine film (35 mm) display system with a Panasonic TV camera (WV 1500). For this device, a 35 mm gray scale resolution pattern (EAI test pattern) was photographed. A cardiac angiographic image was independently evaluated by five radiologists and a test pattern by the four radiologists and one physicist. All four frame grabber images were displayed simultaneously on the E Machine monitor. Board evaluation was based on image sharpness, range of gray scale, and absence of noise and artifacts.

Results

Variations in the ability of boards A,B,C and D to capture a full range of 256 gray shades is shown in Fig. 1. Each board was connected to the video pattern generator and the resulting image was stored. The gray scale ramps are grouped together for comparison.

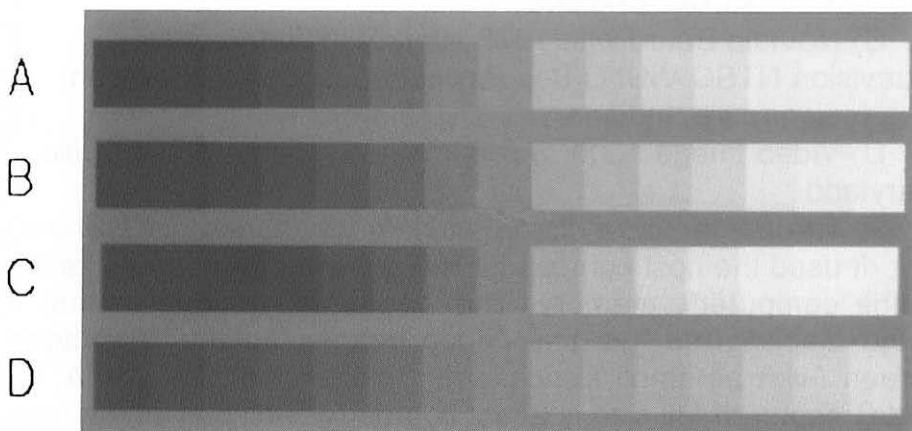


Figure 1. Gray scale ramps generated by boards A - D.

Significant differences between the number of steps and the sharpness of the transitions are shown. While board D displays the widest range of steps, it does not use the full range of 256 values and is noisy. This is illustrated by the profiles (Fig. 2) of the gray scale ramps.

Noise was measured in a rectangular region-of-interest centered on the middle gray step (Table 1, A) and in a dark portion (Table 1, B) of each image. The results are shown in Table 1.

Table 1

	A		B	
	mean	s.d.	mean	s.d.
A	134.91	0.32	211.97	0.88
B	146.10	0.30	221.42	0.53
C	156.68	2.57	233.04	1.53
D	124.22	1.15	192.39	1.37

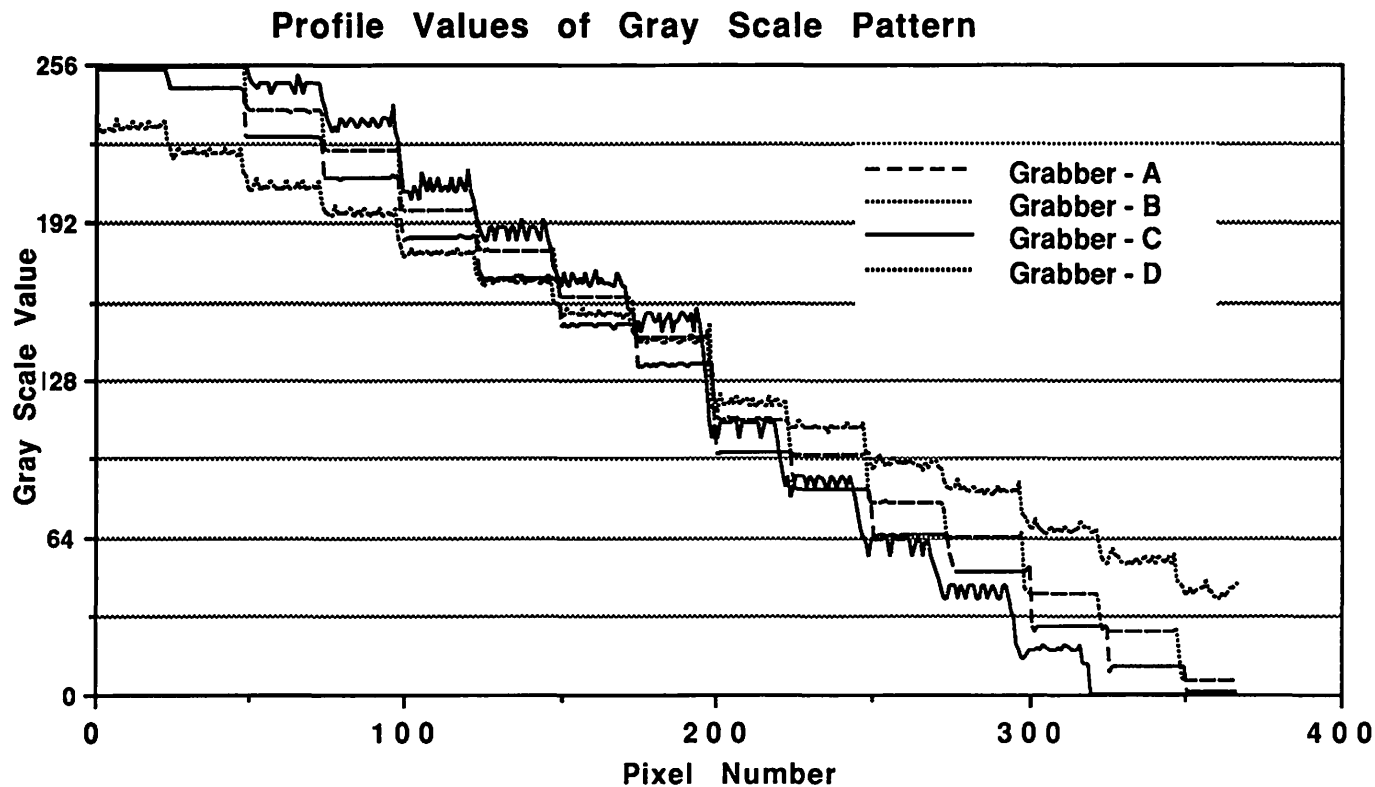


Figure 2. Profiles through gray scale ramps shown in Fig. 1.

A comparison of the ability to resolve lines in the EIA pattern is shown in Fig. 3. Once again there is marked variation among the boards.

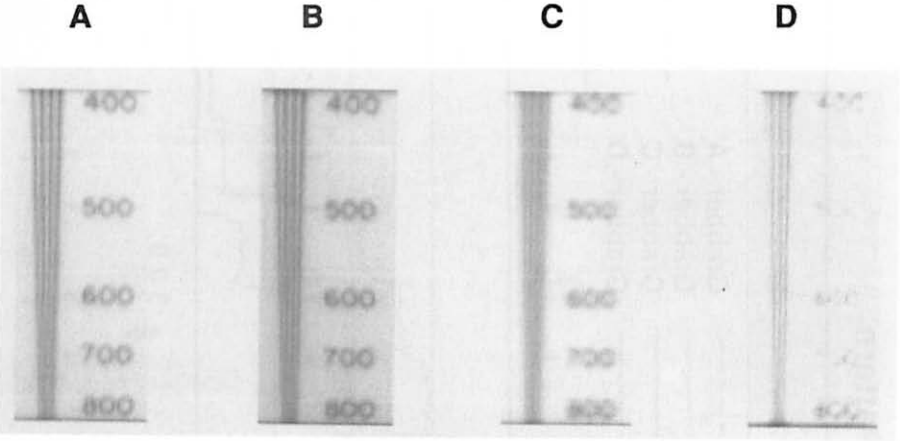


Figure 3. Resolution pattern from boards A - D

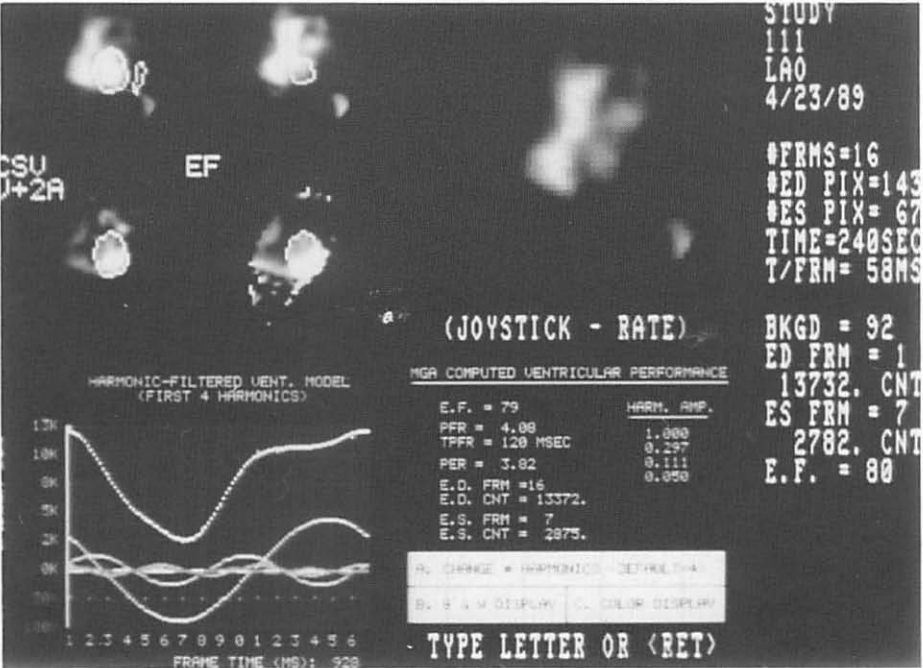


Figure 4. Ventricular performance image (board A).

To test the boards' performance with a nuclear medicine image, a ventricular performance image was generated on the PCS Computer and grabbed by each board (Fig. 4).

Details of the image are shown in Figures 5 and 6. Note in particular differences in noise patterns and resolution.

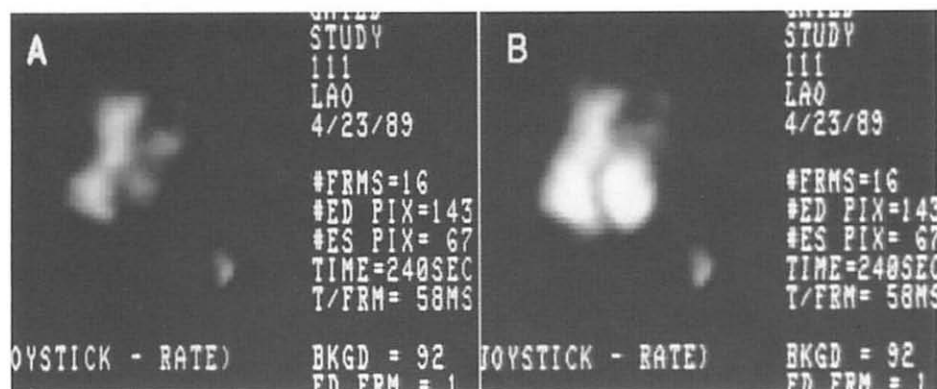


Figure 5. Comparison of boards A and B

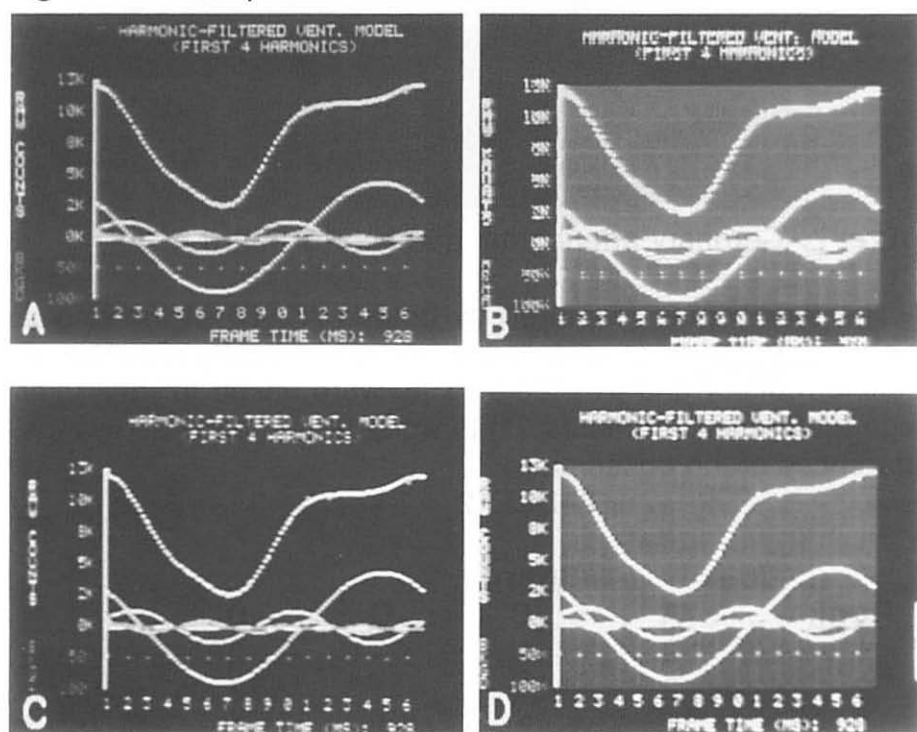


Figure 6. Comparison of boards A - D.

Since the images captured by the boards were going to be used for the analysis of various clinical protocols, a frame from a coronary arteriogram was grabbed (Fig. 7).

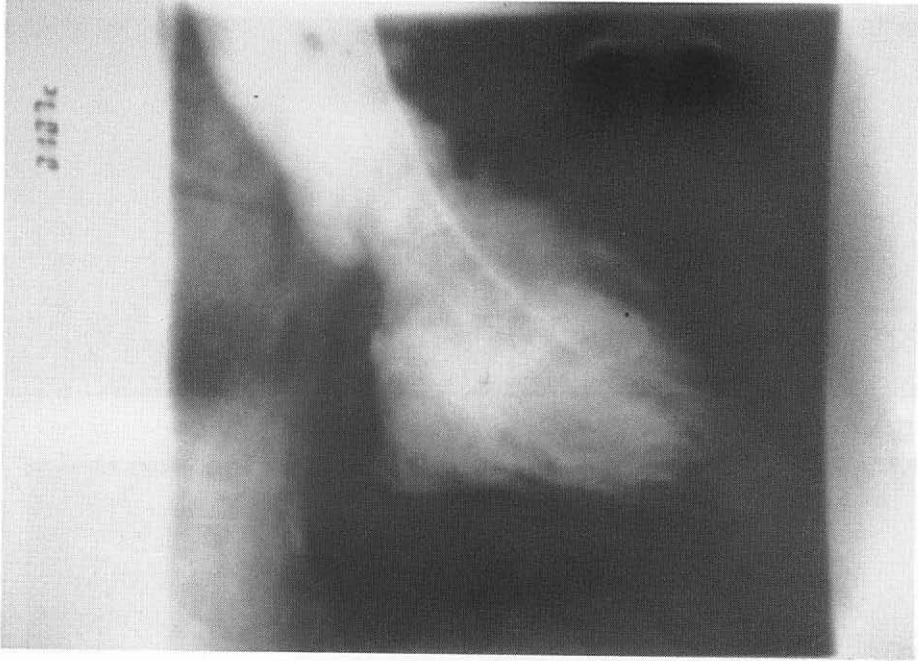


Figure 7. Coronary arteriogram grabbed by board A.

The four copies (captured by boards A - D) of the angiographic image were displayed simultaneously on the E Machine monitor and five radiologists were asked to rank their image preferences from best (1) to worst (4). Table 2 shows the preferences of the observers.

TABLE 2

<u>Rank</u>	<u>Board</u>			
	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
1	2	1	-	2
2	2	1	-	2
3	1	2	1	1
4	-	1	4	

In addition, the video test pattern was displayed in a similar fashion and preferences ranked:

TABLE 3

<u>Rank</u>	<u>Board</u>			
	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
1	4	-	-	1
2	1	2	-	2
3	0	2	1	1
4	0	1	4	1

Discussion

The test patterns revealed large variations in image quality. Problem included excessive background noise, vertical noise patterns, interlacing and synchronization problems. Overall, board A appeared to generate the highest quality images. However, the observer tests showed that viewer preference was an important factor in choosing a board for clinical applications. In general, we concluded that while significant variations existed among the boards, these difference were harder to observe in standard clinical images. For quantification of regions-of-interest and the detection of edges, the best quality images are required from frame grabber boards.

Acknowledgment

We grateful acknowledge the support and cooperation of all the frame grabber board vendors. In addition, the help and suggestions of Charles Harrell and Dr. Philip O. Alderson are acknowledged with appreciation.

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Pilot Study of High Resolution Teleradiology System

Joseph N. Gitlin and Bob W. Gayler

Department of Radiology and Radiological Science,
The Johns Hopkins Medical Institutions, Baltimore, MD

Charles D. Flagle

School of Hygiene and Public Health,
The Johns Hopkins Medical Institutions, Baltimore, MD

The term "teleradiology" refers to the transmission of radiographic images from one location to another for interpretation, review or screening. Most of the work to date, and the most demanding, has involved the scanning of conventional radiographs to convert them to a digital format for transmission and primary interpretation by a qualified radiologist. The review function usually involves the transmission of images with a report for viewing by attending physicians in settings such as the Intensive Care Units in major medical centers. The use of teleradiology systems for screening typically involves the transmission and viewing of images by the "on-call" radiologist in consultation with an emergency physician to determine appropriate care in urgent cases.

At The Johns Hopkins Medical Institutions teleradiology systems are being evaluated to determine their utility within the Johns Hopkins Health System which includes many medical facilities at different locations in the State of Maryland. When the facilities are linked by high speed transmission media, medical images from all types of modalities may be transmitted for many purposes, particularly when a site does not have a radiologist

available and expert consultation is needed. The current pilot study of a high resolution teleradiology system is designed to evaluate each of the components as well as the total system in terms of technical feasibility, clinical acceptability and cost effectiveness.

The specific clinical functions of concern include the provision of diagnostic services to an emergency room in an affiliated hospital that does not have a radiologist available 24 hours a day. The study will also include the sharing of an optical archive specifically designed for digital images from all types of modalities. Digitized film, magnetic resonance images, computed tomography slices, and nuclear medicine scans will be transmitted for storage in the "jukebox", from a film digitizer and from direct digital connections to selected imaging equipment, and retained for subsequent retrieval and display. The pilot study is expected to provide data that will be useful in evaluating the specific equipment comprising the teleradiology system and to gain experience that is pertinent to the design of a comprehensive image management network for the Johns Hopkins Health System.

The major components of the teleradiology system include a film digitizer and a medical imaging gateway at the Francis Scott Key Hospital that is linked by a terrestrial T1 line to The Johns Hopkins Hospital where a medical imaging gateway, high resolution workstation and an image archive are located. The film digitizer is manufactured by DuPont in Wilmington, Delaware and is designed to provide a choice of spatial resolutions at 105 or 210 micron pixels with 12 bits of contrast. This option required the development of a "VDRSC" scanner control board and new software provided by Vortech in Dallas Texas. The medical imaging gateway supplied by Vortech includes local storage, buffer memory and

communication control functions. Vortech's interface to the DuPont scanner is a DR11W connection.

At Francis Scott Key Hospital there is a multiplexer supplied by Potomac Digital to control the flow of data between the medical imaging gateway and the T1 line supplied by the C&P Telephone company. At The Johns Hopkins Hospital there is also a Potomac Digital multiplexer and a Vortech medical imaging gateway with multiple ports. This controls the transmission of digital images to a Virtual Imaging workstation with two high resolution monitors and to an archive containing both magnetic and optical storage that utilizes a Cygnet jukebox and software developed by Vortech. The software that facilitates the user functions for the Virtual Imaging workstation was developed by the Radiology Department at The Hospital of The University of Pennsylvania.

As of this writing, (April 1990) all of the equipment is expected to be in place and operational by May 14th, at which time a controlled study of the diagnostic accuracy of the teleradiology system will begin. Films demonstrating selected abnormalities and matching normal radiographs will be digitized at Francis Scott Key and transmitted to Johns Hopkins for interpretation on the electronic display workstation and for storage on the archive. For each case a comparison of the interpretation derived from the display will be made with the interpretation from the film and the data subjected to an ROC analysis. The study design also includes a comparison of inexperienced and experienced readers in both the display and film modes of interpretation.

Following the controlled study, an open program will be instituted in which consultation regarding any type of medical

imaging examination may be requested by physicians at Francis Scott Key that will be provided by members of the radiology faculty at The Johns Hopkins Hospital. The faculty who will interpret the images on the high resolution display terminal and provide a prompt report. In each case, the original films will be read independently and a comparison made of the resultant report with that derived from viewing the images on the electronic display. Any discrepancies noted between the two reports will be submitted to a Consensus Panel for resolution and the outcome recorded in the pilot study database. Through the controlled and open studies, it is expected that objective data bearing on clinical acceptability will be obtained which in conjunction with a subjective evaluation of the utility of the system by the participating staff will provide definitive results. Preliminary findings will be presented at the Session on Teleradiology at the 10th Conference on Computer Applications in Radiology.

Reporting

Requirements for Reference to Previous Images & Reports When Interpreting Chest Examinations

Steven M. Montner, Heber MacMahon, Paul Davis, et al

Department of Radiology, University of Chicago
Hospitals and Clinics, Chicago, IL

Availability of previous radiological examinations is a valuable asset in interpreting new examinations. Therefore, retrieval of both images and reports of previous examinations is an essential requirement for film file systems or for PACS, and such retrieval functions must be supported by radiology information systems. To gain a better understanding of these requirements, we reviewed the standard clinical practice in the chest radiology section of a teaching hospital with regard to the use of films and reports of previous examinations.

In our practice we found that previous examinations had been performed within 5 years for 48% of the routine PA and lateral chest examinations, and for 90% of portable chest examinations. Although previous images generally are reviewed, it can be helpful to review the reports, particularly when the earlier examinations were interpreted by a different radiologist. Even without PACS, a radiology information system can provide convenient retrieval of previous reports. In our radiology information system, developed at the University of Chicago, all reports for the prior five years are online. The chest reporting module offers a default suggesting that the radiologist review the most recent prior report. Using this system chest radiologists chose to review reports in 36% of the cases in which they were available. An option to display additional prior reports in reverse chronological order allows data to be collected by the system to show the distribution of references to immediate prior reports, second prior reports, etc. Summaries are compiled for individual radiologists to show inter-radiologist variation in reporting style.

Delays in reporting commonly occur due to the need for retrieval of films of prior examinations; we suggest that the incremental cost of providing convenient access to previous reports may be much less than the cost of similar access to images. In summary, accessibility of previous reports, independent of availability of the images, is considered important by radiologists and appears to support improved accuracy of interpretation.

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Augmenting Text with Images in Radiographic Reporting: A Pilot Evaluation Study

John W. Loop and Alan H. Rowberg

Department of Radiology, University of Washington
Medical Center, Seattle, WA

Introduction

Medical records are likely to be more useful if they contain appropriate graphic material. In the case of the radiology report, diagnostic conclusions and recommendations become more convincing when the clinician personally can review the image evidence ("findings") on which these are based. While the x-ray film is the usual source of this evidence, it may not be convenient for the clinician to match it with the report for purposes of confirming the diagnosis, advising the patient concerning his/her health status, performing chart reviews, etc.

Hypothesis

Modern desk-top publishing techniques make it possible to incorporate radiographic images, appropriately selected and annotated, as part of the radiology report. We have postulated that such illustrated reports would be preferred by referring physicians, notwithstanding a significant loss of image detail. A survey of these referring physicians was carried out to determine whether this hypothesis was correct.

Methods

This evaluation was performed on sample reports with integrated images which were produced on a prototype report/image printing system. Most of the production process is slow and labor-intensive on this system, but it is capable of producing reports of the same high quality that can be realized on the more efficient system which would be required for routine clinical use. This long production time was not an impediment to the survey respondents, since they were dealing only with the paper copies of reports which had been

previously produced. The questionnaire was based on partially simulated cases, but was otherwise representative of what reports from a system in routine clinical use could look like.

Reports were assembled on a Macintosh Plus computer, using PageMaker 3.01 (Aldus) as a page layout program and printed on an Apple LaserWriter NT printer, a 300 dot per inch laser printer, over the AppleTalk network. Images and text were prepared separately on other computers and transported to the Macintosh over a TOPS network from an IBM-compatible computer system for integration and printing on the Mac. All work could have been done on PC's if any of them had been connected to a suitable laser printer.

The text of the actual radiology report was downloaded from our DECradiology information system (Digital Equipment Corporation) and saved on a magnetic disk. The text was edited to remove patient identifiers and extraneous information, to change the line length, and to remove line feed characters.

Images were read from the standard archive tape of our CT9800 computed tomography scanner (General Electric Medical Systems) on a PC equipped with a magnetic tape drive and stored on magnetic disk. A program was developed to allow the specification of a window width and window level and store the image in the Tag Image File Format (TIFF) used by many PC and Mac image processing programs, including PageMaker. These images were also viewed on the PC to verify that the selected settings displayed the significant details of the image adequately.

The images were then viewed and cropped on a PC using the Optimas image processing package (Bioscan, Inc.). This could also be used to enhance edges or other aspects of the images, but this was not required for these images.

Initially, the 200 copies of the questionnaire and reports were duplicated by an offset printing process. The quality of some of the offset printed copies was not adequate so the radiographic images were reproduced as laser-printed originals for each questionnaire.

Opinions

A one-page data collection instrument was prepared for distribution to those categories of clinicians whose patients were regularly referred for radiographic examination. Approximately 200 packets

contained the questionnaire and eight radiographic reports. These reports included versions with and without graphic representation of a selected radiograph from the study being reported. When a radiographic image appeared on the report, it was annotated with respect to key findings. Cases included digitized radiographs of a fractured jaw, and a pulmonary carcinoma, as well as computed tomograms of septic brain infarcts, and of a pleural fluid collection.

The clinicians were asked to inspect both sets of reports, and then execute and return the questionnaire. In general three themes were explored:

1. Were the reports with images deemed useful by the referring physicians;
2. What were their current practices regarding review of radiographs or solicitation of personal consultation from the radiologists;
3. Were their practices likely to be changed significantly by the new style reports?

Results

A total of 127 questionnaires were returned within two weeks of their distribution. Most were filled out by surgeons in various specialties, and the balance by physicians or pediatricians.

The group included both young and older colleagues. Only 20% (26/127) had been graduated from medical school for 10 years or less, 45% (57/127) twenty years or more, and 35% (44/127) comprised the intermediate age group (11-19 years).

The response of the clinicians to the reports was even more favorable than expected. Fully 96% either strongly or moderately preferred the report with the image to the one without and 98% felt the printed images helped them understand the radiology report either very much better or some better.

While 83% said the resolution was adequate or nearly adequate for its purpose, 17% thought it needed to be better. None thought the relatively poor image quality made the images nearly useless. The fact that 94% felt the reports with images would be more helpful than the reports alone in explanations to patients is particularly

interesting because this method makes the images readily available in the clinical care setting.

While 92% personally review radiographs of patients with positive findings in nearly every case or in many cases, only 54% personally review the radiographs of patients with negative findings.

Use of the film library was likely to decrease, with only 1% saying it would increase, 43% saying little reduction, and 56% predicting a moderate or drastic reduction in their use of the film library.

Moderate or drastic reduction of telephone traffic with the radiologist was predicted by 56% of responses, and 96% felt the report with images would be moderately or much more useful than present reports in chart review and follow-up clinic visits.

Conclusions

Referring physicians thought the reports with images would be useful to them in several settings. About half of cases now result in the attending clinician having a personal consultation with the radiologist, in our teaching hospital setting. Significant reductions in telephone and film library traffic are likely when images are routinely printed on reports, and efforts to expand our capability to do this printing are now in progress.

Simultaneous Mammography Report Generation and Database Entry

Murray G. Baron and Doris S. Strange

Department of Radiology, Emory University School of Medicine,
Emory University Hospital, Atlanta, GA

The prompt production and delivery of reports is a major problem faced by almost every radiology department. The speed with which this is accomplished depends on many factors, most of which can be optimized with adequate personnel and proper management techniques. The delay that occurs between the transcription of a report and the approval by the radiologist is more difficult to minimize.

The purpose of proofreading reports is two fold: 1) to correct any typographical errors introduced during transcription and, 2) to ensure that the written report is of the correct patient and conveys the radiologist's true impressions. In order for this exercise to be meaningful, not only must the report be read, but the radiologist must be able to associate the patients name and his diagnostic conclusions with those in the report. The more time that elapses between dictation and proofing, and the greater the number of films dictated in the interim, the less likely that the radiologist will be able to recall a specific case. This is not a problem in low volume areas such as interventional radiology or special procedures because few cases are done in a day and the radiologist is involved with each patient over a relatively long period of time. When one radiologist reports 50 - 100 cases a day, review of reports needs to be frequent if it is to be anything other than

grammatical correction.

The problem is compounded in those institutions where the radiologists work at more than one site. Reports dictated in the afternoon are often not returned for signature until the following day. If the dictating radiologist is assigned elsewhere, who signs his reports? Cross-signing by other radiologists will improve departmental efficiency but certainly skirts the intent of the process.

Electronic signature provides a partial solution. It does away with the transport and shuffling of paper and, perhaps, makes it easier to approve reports. If the different sites covered by the radiologists are networked, reports can be approved by the original radiologist wherever he is working - so long as he is not on vacation or away at a meeting. Even with electronic signature, however, the reports still should be reviewed in temporal proximity to dictation so that the cases are not forgotten or confused. Making corrections can be a problem with electronic signature. If the radiologist cannot, or will not type, the report must be redictated and cycled through the entire process one more time.

A simple solution to all of these problems is to have a secretary who can take direct dictation, assigned to each radiologist when he reports. After each examination or so, he can review the report and sign it or dictate necessary corrections on the spot. Eventually, as voice recognition software is refined, it may be possible to accomplish the same thing without a secretary. However, this technology has not arrived as yet.

Another approach would be to shrink the time between dictation of the report and its transcription. This can be done, to some extent, by using a tank dictation system and an adequate number of typists. However, because film interpretation occurs

sporadically throughout the day, it is not practical to set staffing levels according to the times of peak activity. In an attempt to maximize the efficiency of available transcriptionists in our Breast Imaging Center, dictation was replaced with a series of check sheets where each box represents a specific radiologic finding. Each box is assigned a code. The radiologist ticks off the appropriate boxes and the transcriptionist simply enters the codes. A relatively simple computer program automatically concatenates the appropriate phrases to form the report. Unfortunately, this did not solve much. Reports dictated in the late afternoon are still not available until the following day and cross-signing is still required. Furthermore, individual radiologists may feel unsure about the finished reports because entry of a wrong digit may profoundly alter the code and its meaning. As a result, some radiologists require the original check sheet to be returned with the typewritten report so that the two can be compared. This system solves the problem of associating patients with their radiologic findings but does not achieve the hoped for saving of time.

Automated reporting systems do exclude the transcriptionists from the report producing process. They tend to be cost effective and can present completed reports almost instantaneously, thus allowing the radiologist approval before moving on to the next case. Although several comprehensive systems have been available for some time, they have not met with widespread acceptance. This is due in part to the radiologist-computer interface but also because of their limited vocabulary. In some areas, such as chest radiography, the nuances of language are required to properly describe film findings and to influence the clinician's approach to further diagnostic studies and treatment of the patient. Other areas, such

as mammography, angiocardiology and nuclear medicine, deal with a more circumscribed group of diagnostic entities and employ a rather limited descriptive vocabulary thus making them more suitable for computerized reporting systems.

We felt that a graphical computer interface would be most acceptable to the radiologist and ported the check sheets that had been in use for some time to the computer. Multiple screens are utilized for data input. Using the mouse, the radiologist clicks in the appropriate boxes and on pop-up diagrams. The report is produced from an included dictionary of technical phrases. As soon as data entry is completed, the finished report appears on the screen and is accepted by the radiologist by clicking in a password-controlled check box. In our department, this report is transmitted through an Ethernet network to our management system running on a VAX and is printed and stored in the same format as all other radiology reports.

The program was originally written in Hypercard. However, Hypercard is limited in its capabilities as a database. The program was then rewritten in a database language (4th dimension) so that as each box is clicked to generate the report, the radiologic findings are transparently entered into the relational database. We are able to receive pathology reports via a bridge to the pathology Ethernet network and, by copying and pasting, enter them in the database without additional typing. The program is being expanded to include calendar function for patient scheduling, form letter generation to the referring physician and the patient as well as reminders for return visits, at the appropriate time.

A User-Friendly, Radiological-Reporting Workstation

Greg Leeming

CETCO Inc., Providence, RI

John McGibbon

Dimensional Medicine Inc., Minnetonka, MN

Brian W.A. Leeming

Department of Radiology, Beth Israel Hospital,
Boston, MA

Dimensional Medicine Inc. (DMI) of Minnetonka, Minnesota is poised to enter the radiological reporting market with a speech recognition station, the DMI-VRS, that is both natural to use and cost effective. This machine utilizes two recognition systems. The first, the only speaker-independent, continuous recognizer currently deployed in the radiological arena, is used to drive the only mature, menu-driven, radiological knowledge base, Radlex. The second, a natural, speaker-dependent recognition system, is used to provide menu streamlining, freetexting and full digital dictation. All this functionality is provided at approximately one half the price of competitor workstations. This paper describes the capabilities of the DMI-VRS workstation and the philosophy used to design it.

The development of a radiological workstation is primarily an interface design problem. There is much to be gained by making radiological reports available as soon as possible to those who can benefit from them, however, this requires that these reports be entered directly into a computer. Present day computer interfaces are far too cumbersome and sluggish to allow direct entry with reasonable effort, especially by those who are not experienced computer users. Successful workstations will therefore be those that provide intuitive interfaces that do not detract from the productivity of radiologists.

The majority of modern computer interfaces are unnecessarily awkward because they fail to take proper advantage of the years of effort humans invest in language acquisition. To see this we will first lightly delve into the nature of human-human interaction and use our conclusions to expose the shortcomings of modern computer interfaces. We will then discuss how these shortcomings can be overcome using reasonably priced present-day technology. The DMI-VRS workstation will be used as an example throughout this discussion. Finally we will describe the interface improvements that can be expected in the near future given current speech processing research trends.

If two entities are to communicate they must both be privy to the same language system which will have a general structure of the form depicted in figure number 1[1]. The core of this system is a semantic interpreter which allows an entity to extract meaning from the syntactic constructs

(sentences, phrases, etc.) generated by and presented to him/her/it during interaction. The lexicon and the grammar define how syntactic constructs can be legally formed, i.e., what constitutes correct phrase and sentence structure. Finally, the lexical mapping defines how syntactic constructs can be physically conveyed. For example, two humans speaking English use speech as their lexical mapping, i.e., they assign a different sound to each element in the English lexicon, conform to the English lexicon and grammar when forming syntactic constructs and semantically interpret these syntactic constructs using mechanisms which unfortunately are not yet well understood.

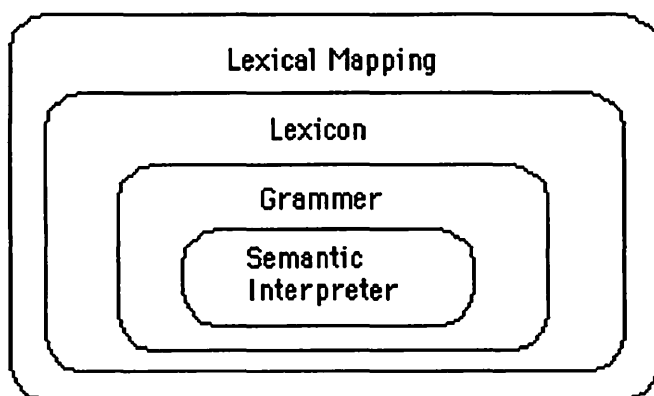


Figure 1: General language structure.

The acquisition of language is a difficult task for humans. Most of us only master one lexicon and grammar, usually English in the USA, and a few lexical mappings, usually speech and reading/writing, in our lifetimes. Speech is the mapping most of us use for face to face communication because we naturally acquire it and because it allows us to communicate rapidly in real time. Read/write mappings are valuable because they allow us to record language, however, such mappings are inefficient for face to face communication, i.e., consider the difficulty of communicating by passing written notes back and forth. Given the large amount of time required to master languages it is little wonder that we resist learning those that define computer interfaces. If computer interfaces are to be truly "user friendly" they should incorporate as much of our native language skills as is technically pertinent. Unfortunately this strategy has not been followed in the design of most present day interfaces.

The languages that define most existing computer interfaces have two major flaws. First, the lexical mappings they utilize are usually reading/writing variants, i.e. inefficient message passing mechanisms. Second, the lexicons and grammars involved tend to be highly restrictive

usually providing only one legal lexical construct per specific computer command, i.e., most commands can only be entered as some exact string of characters. Using reading/writing as the lexical mapping slows down communication unnecessarily. Attempts to correct this problem, the introduction of hot keys, etc., simply replace this problem with another; they cause interfaces to become unsatisfactorily cryptic. We have trouble remembering which key is associated with which command, etc.. Highly restrictive grammars make communication frustrating. Humans are bad at remembering the exact syntax associated with commands. Human lexicons and grammars, on the other hand, are extremely rich. There are usually numerous legal syntactic paths available to communicate any specific idea. This richness allows us to convert ideas into appropriate lexical constructs with relative ease allowing us to fluently converse on the fly.

As an example of a current computer interface consider that defined by MS-DOS, the operating system utilized by IBM in their original P.C. line. The lexical mapping used here is a visual read/write mapping involving the English/Arabic alpha-digits and a collection of other symbols such as slashes, asterisks, etc. This mapping can be extremely cumbersome when entering long commands or in general for those who are not proficient with a keyboard. The rigidity of MS-DOS's lexicon and grammar compound its lexical mapping problems. Even seasoned experts constantly find themselves having to refer to reference manuals to determine how MS-DOS's exacting commands must be entered.

The prevalent solution to MS-DOS type command line interfaces is the graphical interface introduced by Xerox in 1981 (Xerox STAR) and made famous by Apple in their Macintosh line [3]. Such interfaces use lexical mappings which are, in a sense, forms of sign language. The computer presents its operator with a selection of visual symbols, either icons or menu entries, from which the user selects some useful sequence. Sign language implements lexical mappings which are as efficient as speech, i.e., a signed conversation can be carried out at the same pace as a spoken conversation, however, the symbols used in such mappings are not naturally acquired and therefore must be learnt. Visual interfaces do not take advantage of the language skills that the majority of us learn as children: speech and our native lexicons and grammars. Graphical computer interfaces circumvent this shortcoming by visually presenting the user with all of his/her possible options eliminating the need for him/her to memorize them. The problem with this strategy is, of course, that only a very limited number of symbols can be presented to the user at any one time. This is true because of the limited space available on computer presentation surfaces and more importantly, because humans are not capable of scanning large lists of symbols with comprehension in a reasonably short period of time. Submenus provide some relief for this problem but unfortunately tend to slow interaction down.

The solution to these interface shortcomings is to rely more heavily on

our naturally acquired language skills. Computer interfaces must use speech as their primary lexical mapping as well as rich subsets of our native lexicons and grammars. Visual aides such as menus should be used to complement speech where ever appropriate, however, care must be taken to insure that these aides do not detract from interface efficiency. This overall approach will become increasingly important as the complexity of computers increases in the future. Future technology will strain current interface designs beyond their effectiveness.

The DMI-VRS workstation was designed with the above philosophy in mind. The core of this workstation is a rich radiological lexicon and knowledge base known as Radlex. Radlex is a direct descendant of CLIP [6], a lexicon which is the product of many years of research by radiologists working at the Beth Israel Hospital in Boston. The primary lexical mapping deployed is natural speech provided by a pair of recognizers that accept continuous speech and are backed by a flexible grammar. A digital dictation capability is provided for those who do not wish to embrace technology.

Radlex consists of approximately 13,000 menus of data hierarchically organized into large sets each of which is related to a specific body area or system such as the chest or central nervous system. Every data set consists of a master menu which points to numerous submenu sequences which contain phrases that are combined to generate reports. Radlex automatically selects submenus for the radiologist where ever appropriate, guiding him/her through the report generating process. This feature eliminates most of the inefficiencies, eluded to earlier, associated with submenu selection.

A typical Radlex session proceeds as follows. The radiologist is provided with patient demographic data, a space where the report being generated is displayed, and the current Radlex menu. When a selection is made from this menu the computer responds by either appending text to the report presented in the report display area or by providing the user with a new submenu. The end result of this process is the generation of a concise report which clearly describes what ails the patient.

Radlex is thus broadly similar to other existing lexicons. The relative superiority of one lexicon over another is mostly related to its internal structure and how closely this structure reflects everyday reporting styles. In particular the grouping of commonly used statements into a pattern which seems natural to the user and which is repeated wherever possible in equivalent situations is extremely useful. For example, in Radlex every limb menu (shoulder, ankle, etc.) provides normal, no fracture, fracture and fracture follow up as the first four options. A study of 500 limb reports revealed 90% were derived from these four options.

Just as the modern automobile is vastly superior to its early ancestors because of continuous incremental design improvements so the present day Radlex is vastly better than its earlier versions due to the same incremental improvements in design and content. Radlex now has copious

differential diagnosis lists, optimized sets of qualifying words inserted wherever useful and multiple lists of findings related to numerous topics which can be drawn from to justify the conclusions they support. Wherever useful, lists of recommendations are available for inclusion in reports. These improvements endow Radlex with a rich lexicon that is natural, educational and easy to use.

Menus such as those utilized by Radlex can be viewed as two dimensional matrices whose elements can be efficiently selected by stating their row and column numbers. This means that by inputting digits one can take complete control over a lexicon like Radlex in an elegantly simple manner. This strategy has been utilized in the DMI-VRS to provide a basic level of control. Digit input is implemented using a speaker independent, highly accurate, continuous digit recognizer. Speaker independence means that this recognizer does not require any training. Anyone can walk up to the DMI-VRS and immediately take complete control over it as they would if they had hired a human to do their bidding. No initial training session is required. Speaker independence also means that the DMI-VRS is immune to the daily variations that naturally occur in the human voice. Even if one has a severe cold the DMI-VRS will continue to function well. Continuous recognition allows one to enter strings of digits naturally, without pauses in between digits, as one would when conversing with other humans. This naturalness is not provided by most other recognizers.

As stated previously, when designing an interface that uses a menu hierarchy such as that implemented by Radlex, one must take care to prevent inefficiencies that result from the overuse of submenus. The DMI-VRS avoids such inefficiencies in two ways. First, Radlex's automatic menu selection process selects menus for the user where ever possible. Second, a second recognizer, a speaker dependent, continuous recognizer has been integrated into the DMI-VRS to allow user defined streamlining of the menu selection process. This recognizer is constrained by a user definable grammar and is capable of recognizing thousand of user defined words. It allows the user to train the DMI-VRS to recognize key words or phrases which trigger Radlex to automatically progress through desired menu sequences. During normal recognizer operation the user utters requests in natural, continuous human speech. Any user defined words that exist in this speech are recognized. If these words occur in an order that is legal as specified by the user defined grammar, the computer carries out the desired menu sequence. The advantage of this recognizer is that it allows the user to define a rich grammar and lexicon combination which simplify the command input process. All inputs are conveyed using normal conversational speech. This recognizer is also used to implement a freetexting capability which functions in a fashion similar to that described above.

A typical DMI-VRS reporting session proceeds as follows. The radiologist inputs the appropriate accession number using the speaker

Independent digit recognizer. He/she then generates his report assisted by Radlex and using the digit recognizer. If the radiologist has preregistered streamlining phrases he/she may utter these where appropriate to speed up this report generating process. New streamlining phrases may be entered interactively when ever desired. If a freetexting capability has been developed it may also be utilized or amended at any time. If the radiologist does not wish to use Radlex he can opt to completely input his/her report using digital dictation.

Ideally speech processing technology used in computer interfaces should allow humans to converse with their computers as naturally as they do with each other. Unfortunately such technology is at least a decade away [10]. However, the recent wide acceptance of Hidden Markov Modelling, a speech processing technique which produces excellent results, has produced some quality, reasonably priced, small vocabulary recognizers such as the continuous digit recognizer utilized by the DMI-VRS. Predictions are that, due to the embracing of more advanced Markov modelling techniques such as Semi-continuous and Continuous Hidden Markov Modelling, high quality, continuous, speaker independent recognizers capable of recognizing approximately one thousand words will be commercially available in the short term [2,4,5,7,9-10]. Continuous, speaker-independent recognizers with vocabularies containing tens of thousands of words should become commercially viable around the turn of the century [10]. True, human-like interfaces should begin to emerge at this time as complementary advances in semantic interpretation techniques also mature. Until this eventuality the use of small vocabulary, natural recognizers such as those implemented in the DMI-VRS will provide interfaces that are far superior to existing computer interfaces.

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Initial Experience with an Online Speech Recognizer

Lawrence J. Moss

Department of Radiology, University of Massachusetts Medical Center,
Worcester, MA

The Clinical Information Advantages, Inc. (CIAI) RADstation is a state-of-the-art speech recognition system adapted to Radiology. It consists of two layers: the Dragon layer, which comprises the basic speech recognition software, and is based on the Dragon Systems, Inc. speech recognition board, functioning in a high performance 80386-based IBM compatible computer, and the CIAI RADstation software level, which customizes the speech recognizer for Radiology.

The initial clinical trials of the RADstation are under way at multiple sites, under the aegis of the Radiology Information System Consortium (RISC) Speech Recognition Task Force. In addition to evaluating the clinical content and utility, each of the sites have been looking at other aspects also of RADstation integration with department operations. At the University of Massachusetts Medical Center in Worcester, and at the Hospital of the University of Pennsylvania in Philadelphia, the RADstation has been interfaced to the DECrad Radiology information system. At Methodist Hospital in Indianapolis, Indiana, the system is being interfaced to the MAXIfile system; while at Johns Hopkins University Hospital in Baltimore, the interface has been to locally developed Radiology information modules. Operation at the Massachusetts General Hospital in Boston has been as a stand-alone unit at one of the satellite facilities. The clinical areas exercised at each site have been dependent on the clinical interests of the particular radiologists using the RADstation at each site.

In comparison with earlier speech recognition systems, the RADstation is speaker-independent, but trainable. This means that the average user can go to the RADstation, take the microphone and have a large percentage of his speech recognized immediately, without having to resort to preliminary training. Some of the earlier systems required training the system fully for each and every word that would be spoken by the individual user. The RADstation, however, begins with a general speech model able to recognize a large percentage of what is spoken. Through use, the RADstation becomes speaker-dependent, training itself to the individual speaker's voice, accent, and inflections. Thus, the average user can begin using RADstation almost immediately to produce reports. A fair amount of easily correctable misrecognition or questionable recognition can occur at first, using the RADstation; this slows the user considerably, during the initial phases. This is the learning curve for the machine. The learning curve for the user involves becoming familiar with the menus, their structure, and flow.

There are two dictation modes available: free text dictation and structured dictation. Free text dictation is just that: the RADstation takes each word as it is spoken and builds the text. Structured dictation is the mode where trigger phrases are used, macro style, to generate complete phrases or phrases with blanks that can be filled in. This theoretically results in greater efficiency of dictation, producing multiple words per utterance instead of one. However, there is a significant learning curve for structured dictation until the user learns the menu structure for this mode. Further, there is the problem of not finding the phrase that expresses exactly what the user wants to say the way he wants to say it. The two solutions to this problem are either to accept the existing phrasing or to switch to free text dictation.

The very early clinical experience with RADstation has not been without problems. Some of these problems are conceptual, some are due to performance limitations of the RADstation, while others are "bugs". I hope that most of these will be addressed before the RADstation ends clinical testing.

In the area of conceptual problems, I would include issues of data flow and user interface. At the start of a dictating session, the individual user logs onto the RADstation, identifying himself with a password. However, to complete each report after dictating, it is currently necessary for the user to again type in his password at the keyboard. He then tells the RADstation to sign the report. This is an unnecessary step. The security identification was performed when the user logged on.

Signing of the report, however, does not dispatch it to the receiving systems (except perhaps in the stand-alone RADstation). Because the information systems are constantly uploading header information for each individual patient exam, the RADstation developers elected to hold the dispatching of completed reports until the user ends his RADstation session. Thus, as currently configured, the RADstation does not dispatch reports in real-time.

Because of the word recognition process and the necessity of the radiologist to constantly monitor which words are being put down by the RADstation as dictation progresses, use of the RADstation does not occur in the heads-up mode where the radiologist is looking at the films as he dictates. He has to be concentrating on the screen as each individual word appears in free text dictation, because subtle misrecognitions can always occur. In structured dictation, it is necessary to monitor the screen to know where you are in the menu structure and what the choices are. Most radiologists normally function in the heads-up mode.

A related point involves the microphone system itself. Currently, the microphone is worn over the ears with a hand-held on/off switch to start and stop dictation. This is cumbersome, because putting the microphone on and off is a nuisance; one cannot just put it down between cases; it has to be removed to use the telephone; and the current hand-held dictate switch (a standard toggle switch) is not only clumsy, you have to remember which way it is thrown. Much more desirable and much more in keeping with the way radiologists work would be an adaptation of a standard dictation system microphone that can be picked up from the counter, held to the mouth for dictation, and placed down when not in actual use, having a push-to-dictate button on the microphone and perhaps arrow keys to direct the cursor within the screen, if necessary.

The RADstation has considerable promise of being a valuable tool for working radiologists, and I hope to have more clinical data available at the time of the meeting.

Beta Test of Radiology Reporting System Using Speech Recognition

Joseph Gitlin, Scott O. Trerotola

Department of Radiology & Radiological Sciences,
The Johns Hopkins Medical Institutions Baltimore, MD

Since the establishment of radiology as a medical specialty in the United States, radiologists have been concerned with providing a formal report of their interpretations of medical images to referring physicians, and in the case of hospital practice to the medical records department. When competent medical transcriptionists were readily available and technology had no other options to offer, the common procedure used to produce a formal report was dictation, transcription, review, edit (and correction if necessary), signature and delivery. Under the best of circumstances, this process usually required four hours elapsed time from the performance of the examination to the availability of the report to the referring physician, and it was not uncommon for the process in large urban medical centers to take as long as forty hours. Lengthy delays between the performance of a radiographic examination and the availability of the report caused further degradation of the process by increasing the number of telephone calls to radiologists and necessitating visits by referring physicians to the radiology department to obtain a prompt interpretation.

For the past twenty five years many clinicians, scientists, and workers in fields related to the practice of radiology have attempted to design and implement systems to

facilitate prompt reporting without increasing the burden on the radiologist. Such systems have ranged from the relatively simple process of assigning codes to appropriate pre-structured reports, to complex computer-based systems requiring interfaces with radiology and hospital information systems to provide electronic display and/or hard copy reports for authorized personnel. In the latter group, the early efforts included a system developed by Inger Brolin in Sweden that required keyboard entry by the radiologist on a Saab terminal. A similar approach was developed by Gwilym Lodwick and associates at the University of Missouri, which utilized an IBM terminal with keyboard entry by the radiologist. The RAPORT system developed by Richard Mani involved "mark-sense" cards that were used by radiologists and read by a scanner to produce hard copy reports. At Johns Hopkins, a lexicon containing the terms and phrases needed to report diagnostic interpretations was organized for use by radiologists working with touch entry devices that displayed the appropriate frames for the examination being interpreted. The results of this work were made available commercially in 1976 in a system called SIREP.

The most recent efforts to develop a system that generates a complete, signed interpretation for referring physicians and medical records departments involves the application of speech recognition technology to the radiology reporting functions. With the advances in microprocessors and in high-density storage devices at relatively low cost, several companies have produced commercial versions of radiology reporting systems based upon speech recognition that are used in a variety of clinical settings. While these early efforts have certain limitations, particularly with regard to speaker dependence, and preclude continuous speech input, the prospects for improvement are most promising.

In order to contribute to the state-of-the-art and to provide additional options to radiologists concerned with prompt reporting of interpretations, the Radiology Information System Consortium (RISC) reached an agreement with Clinical Information Advantages, Inc. (CIAI) to develop a cost-effective system based upon speech recognition technology developed by Dragon Systems, Inc. The agreement provides for the professional requirements and functional specifications to be supplied by RISC with the software development the responsibility of CIAI. Following laboratory testing of the initial programs by CIAI, clinical testing was begun in several RISC member institutions. The term beta testing applies to the current activities underway at five RISC hospitals where radiologists who have contributed to the development of "structured" modules dealing with specific body system or anatomical/imaging modality modules participate by reporting clinical cases. In addition to the structured approach, a free text option and customized terms and phrases have been programmed that may be used independently or in conjunction with one another to facilitate the reporting process.

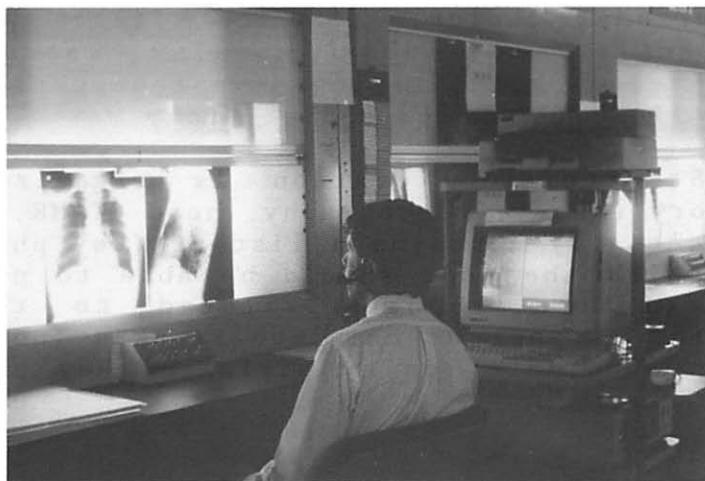


Figure 1.

The reporting system, called RADStationTM, consists of a 386/33 MHz IBM compatible PC with 12 MB RAM, a VGA monitor, and a printer which varies with the participating institution. It can operate as a free standing unit or can be interfaced with several radiology or hospital information systems. At Johns Hopkins the test units are interfaced to the hospital information system (HIS). In addition to the keyboard, the system is equipped with a mouse and a unidirectional headset type microphone.

Patient identification information on cases to be reported (headers) can be entered directly into the system or may be obtained from the HIS. Headers may be retrieved in a variety of ways; by accession number, patient's last name or by history number. In addition, headers may be sorted by date, exam type or alphabetically. At Johns Hopkins, an accession number is used to retrieve a specific header.

Two different methods of dictation may be used to generate the report: a menu-driven format (structured dictation) and free text. The two methods are complementary. Typically, structured dictation is used to report normals and common findings. This mode provides for the introduction by the user of customized phrases of personal choice. The free text mode is frequently used when complex cases are encountered or to supplement a report produced initially by structured dictation.

Structured dictation is organized by category (chest, mammography, head CT/MR, etc). Each category contains a list of (key phrases) with which the user should be able to produce most of the reports related to routine practice; either as complete reports (normals, common abnormalities) or by stringing key phrases

together to form a report. Key phrases are grouped either anatomically or in selected instances pathologically; corresponding to the usual radiological approach to the type of examination. These groups are called "features"; there are usually 8-12 features per category, with 10-30 key phrases per feature. Certain features (complete reports, introduction, clinical history, impression and recommendation) remain constant in all categories but contain different key phrases for the specific category.

To create a report in structured dictation, the user utters the name of the desired feature and then the desired key phrase. Menu choices are made from within the key phrase. A single utterance usually results in a five word sentence, frequently much greater. For example, saying the word "normal" may generate a full page complete report. It is this parsimony of utterances combined with excellent speech recognition, that makes structured dictation a valuable tool.

The ability to customize one's own key phrases is a valuable adjunct to structured dictation. The customization feature can be entered at any time to create a new key phrase or delete an existing one. Thus, one can personalize the system with preferred reports and phrases.

When a case is too complex for structured dictation, or whenever the user prefers, the free text mode may be used. In free text dictation, the user utters one word at time, drawing from a vocabulary of up to 30,000 words. The speed and accuracy of free text dictation has yet to be established, but preliminary results are highly favorable. At Johns Hopkins, several users dictate almost exclusively in the free text mode, attesting to its performance.

Within the system, training occurs in three different ways. It is important to note that no speech recognition training is required before use of the system is attempted. As soon as a user is added to the system reporting of cases may begin. Training occurs "on the fly" and as a user gains experience speech recognition improves. In the free text mode, if a word is misrecognized, the user types the first few letters of the correct word until it appears on the screen and then continues dictating. This "on the fly" training allows the system to relate syntax to recognition, as well as the speech pattern for a specific word. Thus, free text speech training occurs every time free text is used.

In structured dictation speech recognition training occurs only when the user initiates it, by saying "scratch that" to delete a misrecognition, then saying "train this word" to activate the training mode. Again, the first few letters of the correct word are typed until it appears. Then a function key corresponding to the correct word is pressed and the system trains that word. In the third approach, a user can invoke a feature called "retrain words" that allows specific words to be trained in structured dictation. This function is particularly helpful when the user is experiencing misrecognition problems between similar words.

Once a report is complete the user can verify its accuracy on the screen and then by saying "end dictation" may "deliver" that report. A variety of levels of security exist (preliminary reports for residents, final reports for attendings) depending on the local use of the unit. Hard copy is then generated locally and electronic copies are transmitted to the HIS for distribution.

As of this writing (April 1990) the results of the beta test are not available. Those that are documented will be presented at the Session on Reporting at the 10th Conference on Computer Applications in Radiology.

Automated Characterization of Breast Tumors in CR Mammograms

Nobuyoshi Nakajima, Wataru Itoh, Masamitsu Ishida, et al

Miyanodai Technology Development Center,
Fuji Photo Film Co., Ltd., Kanagawa, JAPAN

Introduction

A number of digital radiography systems are recently available for clinical studies. In particular, the clinical use of Computed Radiography(CR) system using photostimulable phosphor imaging plate has been increasing in diagnostic radiology as a new modality which has potential to replace the conventional screen-film system.^{1,2}

Furthermore, one of the future potentials of CR system is likely to be in the fields of Computer-Aided-Diagnosis(CAD). The American Cancer Society has recommended the use of mammography for screening of women with annual examinations over the age of 50, so that mammography may eventually constitute one of the highest volume of x-ray examinations interpreted by radiologists³ For this reason, evaluation of breast tumors in mammograms are recently one of the most important topics in diagnostic radiology. If computerized quantitative methods can be developed which provide the reliable measures to discriminate between malignant and benign tumors as an objective assessment, it is likely that the accuracy of radiological interpretation would greatly increase. We are preliminarily investigating an application of CAD involving an automated method for calculating physical characteristic measures of breast tumors in CR mammograms.

Materials and Methods

Digital image data of mammograms are directly acquired by means of Fuji Computed Radiography system. After the x-ray exposure, the photostimulable imaging plate are scanned by laser beam and the detected photostimulable luminescence radiation are converted to digital image data with a 0.1mm pixel size and 10 bit density resolution. The image data are transferred to a SUN3/260 computer(Sun Microsystems, Mountain View, Calif.) through the dedicated optical-disk filing system for FCR system.

Some features of malignant and benign breast tumors are summarized in Table 1. The basic principle of our method in order to convert these subjective features into objective physical measures is shown in Figure 1. A square ROI including a region of breast tumor is selected by a manual method according to the tumor size.

The image data variation observed in a selected ROI consists of not only tumor signals but also structured background and noise components. Therefore, bandpass filters are applied to the ROI in order to remove the structured background trends and the noise effects due to mammary glands and x-ray quanta, respectively. Next, a polar coordinate transform is employed to the ROI for the purpose of effectively extracting the data variation observed along tumor surrounding.

The power spectrum after the polar coordinate transform are obtained by a two-dimensional fast Fourier transform. Finally, the root-mean-square(RMS) value and the 2nd moment of the power spectrum in Rs direction(Rs') and θs direction($\theta s'$) are calculated in order to discriminate between benign and malignant tumors. RMS value quantifies the magnitude of tumor internal variation. Rs' value and $\theta s'$ value, which represent the 2nd moment of the power spectrum in each direction, quantify the fineness of tumor internal variation and tumor surrounding variation, respectively.

Results

The analytical results of our method are shown in Figure 2., which are obtained from the typical malignant and benign breast tumors in CR mammograms. Malignant tumor pattern has a higher frequency component in both directions of power spectrum and a larger RMS values compared with benign tumor pattern. As a preliminary study, the results of 29 images containing 14 malignant tumors and 15 benign tumors are shown in Figure 3. It is indicated that RMS variation and the 2nd moment of the power spectrum of malignant tumors are clearly different from those of benign tumors.

Discussion and Conclusion

The elimination of background trends and noise effects is a very important step prior to the computation of those physical characteristic measures, because it removes the effect of the undesired data variations and thus makes it possible to isolate the finely detailed pattern due to breast tumors from the overall breast density variations. Moreover, a polar coordinate transform is very effective to extract the data variation obtained along tumor surrounding, so that the combination of the RMS value and the 2nd moment of power spectrum in θ s direction more clearly discriminates between malignant tumors and benign tumors.

We have developed an automated method for determining physical characteristics of breast tumors in terms of the RMS value and the 2nd moment of power spectrum of the breast tumor patterns, which represent the magnitude and fineness of internal structure of breast tumors, respectively. We conclude that these physical characteristic measures calculated from CR mammograms may be useful to radiologists in their differential diagnosis of breast tumors.

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Table 1. Features of malignant and benign breast tumors

	Shape	Border	Internal	Calcification
Benign	regular round oval lobulated	smooth	dense homogeneous	single coarse multiple round
Malignant	irregular starlike stonelike crablike	irregular ragged obscure spicula tentacle	dense non-homogeneous	numerous variable starlike linear

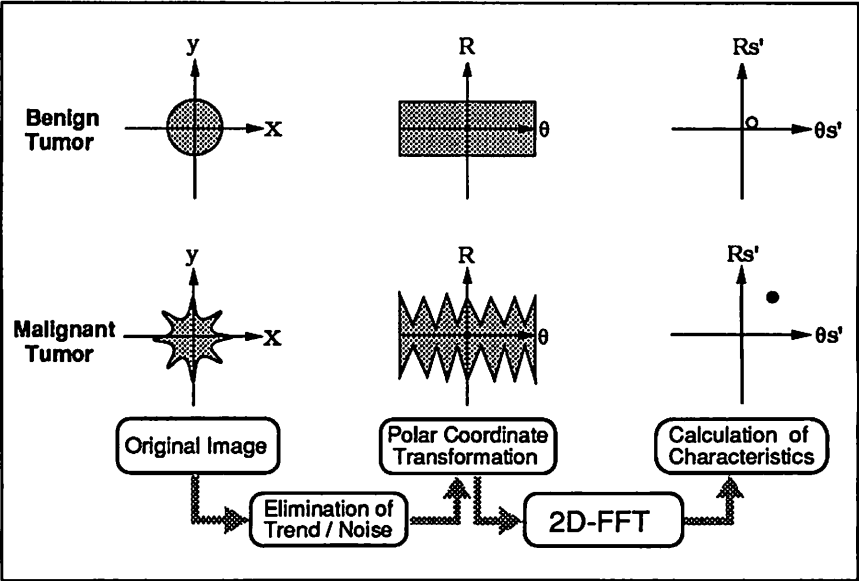
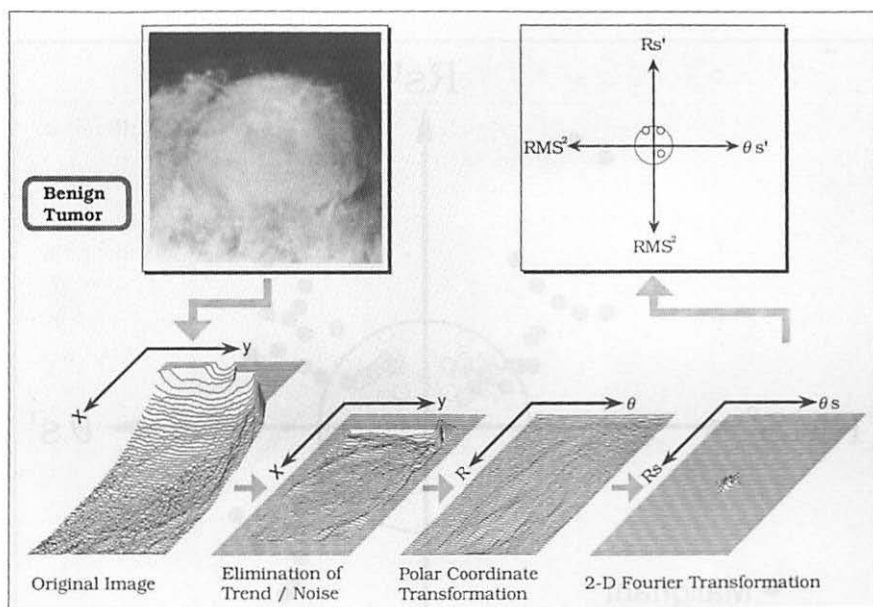
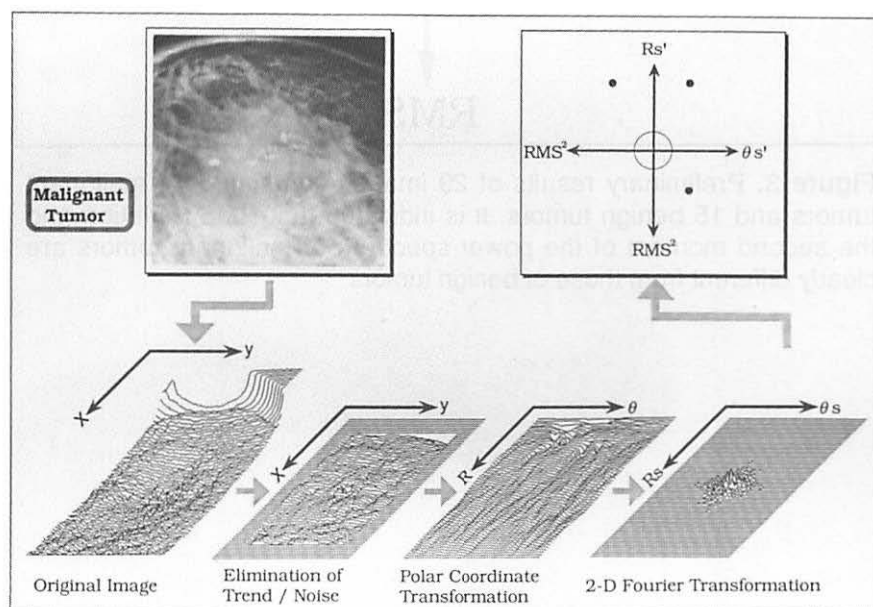


Figure 1. Basic principle of the automated method for calculating an objective physical measures of breast tumors in CR mammograms.



(a)



(b)

Figure 2. Analytical results by means of our method. (a)Result obtained from the typical benign breast tumor. (b)Result obtained from the typical malignant breast tumor.

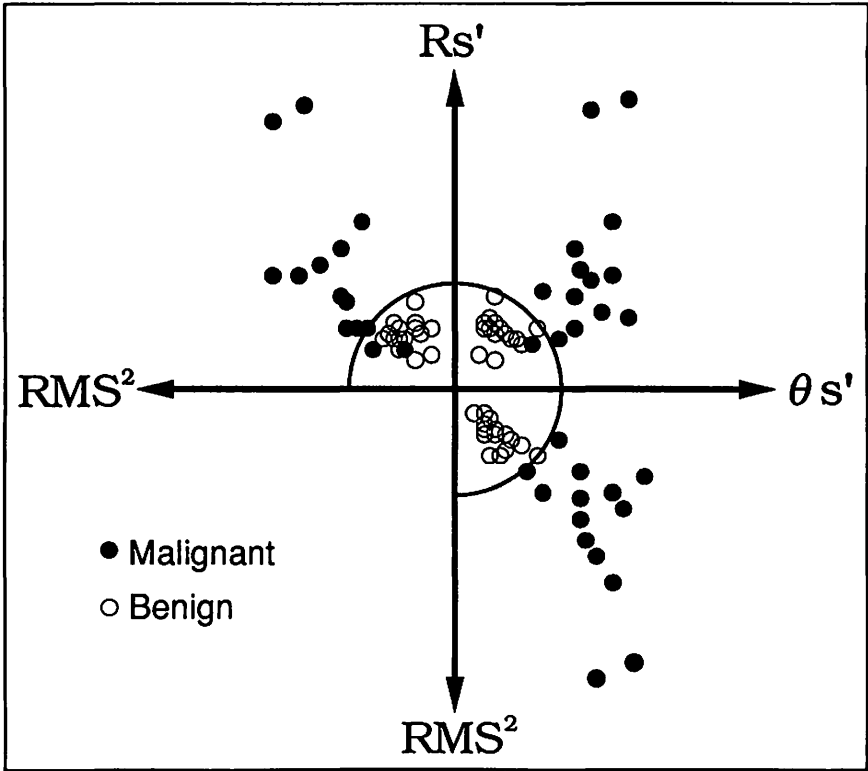


Figure 3. Preliminary results of 29 images containing 14 malignant tumors and 15 benign tumors. It is indicated that RMS variation and the second moment of the power spectrum of malignant tumors are clearly different from those of benign tumors.

Artificial Intelligence

Applications of Artificial Intelligence in Radiology

Kenneth Levin, MD

Division of Nuclear Medicine, Georgetown University Hospital,
Washington, DC

expert system dev.

Abstract

This paper reviews the application of artificial intelligence (AI) in diagnostic imaging. All current and anticipated applications are briefly discussed. A basic understanding of radiology and artificial intelligence is assumed.

Introduction

Applications of AI in diagnostic imaging can be divided into three categories: 1) Applications that involve the acquisition, display, and analysis of images; 2) Applications that attempt to analyze, critique, and improve the cognitive skills of radiologists; and 3) Miscellaneous applications. See Table I.

In this report, a distinction is made between advice programs (AP) and front-end programs (FEP). Advice programs include expert systems (ES), neural nets (NN), statistical programs, and others which use ordered lists of primitive features as input; output is advice (1). Front-end programs use image or numerical data as input and provide a list of primitive features as output. This output is suitable input to an AP. Sometimes a human acts as the FEP providing the input data in an interactive session with a computer, and sometimes a program acts as FEP.

In the future, many of the programs discussed in this article will be components of radiology workstations. These systems, still in the developmental stage, will include picture archiving and storage systems, radiology

information systems, and computerized advice and critiquing systems. There will be user interfaces designed to ease: 1) the acquisition of the radiographic report, 2) image manipulation, and 3) interaction with the other components of the system (2).

On occasion, it is difficult to make a distinction between those programs which use artificial intelligence methodologies and those that use related but non-artificial intelligence techniques. For the purposes of this discussion, all AI programs or closely related programs that serve similar functions are discussed regardless of methodology. I regret any omissions of reports of systems of which I am unaware.

Imaging Applications

Test Ordering

As imaging technology becomes more complex, it is becoming increasingly difficult for non-radiologists to know the appropriate sequence of radiologic test(s) to order for a particular patient. The PHOENIX Radiology Consultant (3-5) is an expert system that offers advice to physicians ordering diagnostic imaging procedures. This system provides an "appropriate, sequential work-up for a variety of common clinical problems". Another AI approach has been described (6). There have been non-AI computerized approaches to the problem of test ordering, (7-9) as well as several handbooks published recently (10-11).

Test Performance Advice

Computed tomographic and magnetic resonance scanners are complex devices. Many variables must be determined before performing an exam. There is a report of an AI system to set up magnetic resonance protocols. (12)

Machine Vision

The perception of features (in an image) by

computers is termed machine vision. Since many of the images in radiology are digital, the distinction between machine vision systems and pattern recognition programs is not clearcut. Both types of programs are considered to be FEP. Their outputs can serve as input to an AP.

Expert Systems

The analysis of image features to suggest a diagnosis has been performed by several expert systems (13-14). In some of these systems, the radiologist acts as the front-end program (15-21). In others, the input is the raw image data, and the front-end program and expert system are internal components of the system (22-27). These are summarized in Table II. Most of these programs are not available commercially. However, there was a brief notice describing the View Station 500 by Streometrix, a system that assists radiologists in interpreting mamograms (28). Claims were made that clinical studies show a 95 percent accuracy rate.

Neural Nets

Neural Nets have recently generated renewed interest. Along with expert systems and statistical techniques, these systems are viewed as a type of computerized advice system which may be part of radiology work stations. I am unaware of any reports of neural networks in any Radiological Advice Program.

Quality Control

AI programs can play a role in quality control. Todd-Pokropek has described a system which uses an expert system as part of a quality assurance computer program in Nuclear Medicine (29). This uses input data from flood field images and other quality control procedures. A front end program transforms this data into primitives which act as input to an expert system. Another system has been described to aid repair personnel in repairing computerized tomographic scanners (30).

Cognitive Applications of AI

Analysis of Radiographic Decision Making

When a radiologist examines a X-ray and interacts with an expert system supplying the findings on the film, he is serving as a "front-end program". It is believed that it is possible to measure aspects of his performance as a front-end program. Likewise, asking the radiologist his diagnosis after examining the film, one would be able to measure his performance as an "advice program". While this separation is artificial and not necessarily how radiologists perform their tasks on a daily basis, it is a way to measure the relative contributions of perception (i.e., as FEP) and reasoning (i.e., as AP) to the radiological decision making process (31). This has been studied on a limited basis (21). In order to perform this analysis, a validated expert system and test case database are required (32).

Critiquing Radiologists

Swett, et.al., have demonstrated the utility of expert systems for critiquing the diagnoses of radiologists (33). In this system, the radiologist interacts with the computer by supplying history, pertinent findings on the image, and a diagnosis. The expert system then analyzes these data and critiques the proposed diagnosis. This system has been extended so that in addition to critiquing the performance of the radiologist, it makes available illustrative radiographic examples both of the findings and of the criticisms that the computer has made of the radiologist's actions. These close the feedback loop (34).

Teaching and Testing

Two unexplored applications of AI in Radiology are teaching and testing. One might argue that the approach of Swett, et.al., discussed above is a form of teaching and may result in increased knowledge of the user.

However, there is also a role for drill and practice in radiological education. The database of cases necessary for an expert system's development can be used as examples for training. In a similar fashion, this same set of cases could be used to compare a new observer's responses with the database of "true" findings and could be used to assess the skill of radiologists.

Miscellaneous Uses of Artificial Intelligence

Robotics

Robots were introduced into the medical laboratory in the early 1980's (35). Subsequently, robots have been used in the preparation of radiopharmaceuticals. This allows volatile chemicals to be used and critical reactions to be performed without excess radiation exposure to humans (36-28).

* Natural Language Understanding

The principal application of natural language understanding systems in Radiology is automated report generation. Kurtzweil and others have demonstrated automated speech understanding systems that use vocal input and produce a typed report. The Kurtzweil system is currently capable of understanding 5000 words from several different users (39-40). It is possible to FAX these reports to the referring physician's office as soon as signed (41). Other systems are under development (42-43). It is also possible to use natural language understanding systems to allow vocal control of devices (44). The availability of PC-based speech recognitions systems should allow continued development of these applications (34).

1
"beb. where time has come.."

Table I.

Outline of the applications of Artificial Intelligence in Radiology used in this paper.

- A. Imaging applications
 - 1. Determining which test to order
 - 2. Determining how to perform a test
 - 3. Machine vision
 - 4. Expert Systems
 - 5. Neural nets
 - 6. Quality control
- B. Cognitive applications
 - 1. Analyzing radiological decision making
 - 2. Critiquing radiologists
 - 3. Teaching (CAI)
 - 4. Testing
- C. Miscellaneous applications
 - 1. Natural language understanding - report generation
 - 2. Radiopharmaceutical preparation

Table II

A List of Expert Systems for Radiologic Diagnosis.

<u>Method Operation</u>	<u>Domain</u>	<u>FEP</u>	<u>AP</u>	<u>Ref</u>
Production rule	Neuro CT	F	T	15
Statistical/rule	Arthritis Hand Films	F	T	16
Prolog	Focal Bony Lesions	F	T	17
Production rule	Mamograms	F	T	18
Statistical	Neuro CT	F	T	19
Knowledge based	Nuclear Renogram	F	T	20
Expert System	Gastric Ulcer Dx	F	T	21
Expert System	LV Wall Motion Angio	T	T	22
Cost Function	Nuclear Gated Blood Pool	T	T	23
Expert System, Fuzzy Logic	Nuclear Gated Blood Pool	T	T	24
Production rule	Ex Thallium	T	T	25
Maximum Likelihood	Neuro MRI	T	T	26
Rule-based Dempster Schaffer	Ex Thallium	T	T	27

FEP = Front-end program, AP = Advice Program,
REF = Bibliography entry

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Modified Observer Performance Study of an Image Interpretation Expert System

^{MD}David Piraino, ^{MD}Bradford Richmond, ^{PhD}Mark Schluchter, et al
Cleveland Clinic Foundation, Cleveland, OH

ABSTRACT

The Radiology Image Interpretation System (RIIS) is an expert system used to study applications of expert systems to radiographic image interpretation. The system takes a description of the radiographic abnormalities of a focal skeletal lesion and, through interactive questioning of the physician, produces a list of the most likely diagnoses. RIIS uses both a rule based approach and a match and score technique to produce the list of the most likely diagnoses. The diagnoses are ranked according to the relative likelihoods produced using the match and score technique. An observer-performance study was done comparing the efficacy of RIIS on a known set of abnormal and normal cases. Modified receiver operating characteristic (ROC) curves for inexperienced residents, experienced residents and RIIS were generated using radiographs of known focal bone abnormalities. On the average, the RIIS system was less accurate when compared with experienced and inexperienced residents. This difference was not significant for inexperienced residents. RIIS performed better than inexperienced residents when used by experienced residents.

INTRODUCTION

Expert systems have been applied to a wide variety of medical problems [1]. Several investigators have been studying the application of expert systems to radiographic image interpretation and consultation [2,3]. One problem with the application of expert systems to image interpretation is that most of the present systems rely on input into the system in the form of findings on a radiograph. If the observer is inexperienced, the input can then be inaccurate leading to inaccurate differential diagnoses [3].

ROC curves are used to study the accuracy of signal detection. They have been used in evaluating the accuracy of many diagnostic systems [4]. The application of observer-performance studies to expert systems has been limited [5]. ROC curves allow comparison of observers and modalities over the complete range of false positive values and are therefore useful in evaluating expert systems.

RIIS was developed to study the application of expert systems to radiographic image interpretation. RIIS interactively questions the user about the findings on a radiograph. The sequence of questions and which questions are asked depends upon answers to previous questions. RIIS makes several intermediate conclusions using a rule based approach. These intermediate conclusions are used to classify a broad category of differential diagnoses. Differential diagnoses in the most likely category or categories are then considered for the final differential diagnosis.

A match and score approach using relative frequencies and relative predictive values of specific findings for a specific diseases is

used to rate the relatively likelihood of each disease. This approach is modeled after the Internist program [6]. Diseases are then put in order according to their relative likelihoods. At present the expert system is limited to focal bone abnormalities.

This study evaluated RIIS using an observer-performance study with radiology residents of different experience.

METHODS AND MATERIALS

Fifty seven cases of known focal bone lesions and ten normal cases were reproduced as black and white prints. The reproductions were used as test cases for RIIS and the radiology residents. The abnormal cases were selected from the Cleveland Clinic Teaching File and each had a known pathological diagnosis. The normals were selected from routine clinical exams considered normal by a musculoskeletal radiologist.

Four residents or fellows with at least three years of radiology training were the experienced residents. Four residents with less than one year of training were the inexperienced residents. The users first select their own differential diagnosis of a case from a list of diagnostic possibilities including normal. Each diagnosis could be selected with a confidence level from 0 to 100 with increments of 10 (0- definitely not the diagnosis, 100- definitely the diagnosis). RIIS was then used by the same resident to produce a differential diagnosis for the same case. The resident's diagnoses as well as RIIS' diagnoses were automatically saved.

ROC curves were constructed by calculating the true positive rates (true positive

number/(true positive number + false negative number)) and false positive rates (false positive number/(false positive number + true negative number)) for RIIS and the residents. The resident's and RIIS' decisions were clarified in four alternatives:

1. true positive decision, decision is the true positive or pathological diagnosis;
2. false positive decision, decision is not the pathological diagnosis;
3. true negative decision, decision that is not the pathological diagnosis is correctly avoided;
4. false negative decision, the pathological diagnosis is not made.

The true positive rates at false positive rates of 0.02, 0.05, 0.1, 0.2 and 0.5 were calculated from each specific ROC curve. These true positive rates were then compared.

RESULTS

The average difference between the resident's true positive rates and RIIS' true positive rates with that resident are presented below.

Average Differences Between RIIS and Residents at Different False Positive Rates

False Positive Rate	Average Difference (Computer Experienced Resident)	Average Difference (Computer Inexperienced Resident)
0.02	-0.24 S.D. 0.09	-0.12 S.D. 0.07
0.05	-0.1 S.D. 0.10	-0.12 S.D. 0.12
0.10	-0.13 S.D. 0.10	-0.05 S.D. 0.12
0.20	-0.11 S.D. 0.06	-0.02 S.D. 0.12
0.50	-0.07 S.D. 0.04	-0.02 S.D. 0.07

On the average RIIS did not perform as well as experienced or inexperienced residents. This difference between the user and RIIS was marginally significant for experienced residents at a low false positive rate, but was not significant for inexperienced residents. RIIS' performance with experienced residents was better than the performance of inexperienced residents alone. Experienced residents also outperformed inexperienced residents.

DISCUSSION

Evaluation of medical expert systems is difficult [7]. Expert systems must be

evaluated in order to judge their effectiveness in the medical environment. This study demonstrated that RIIS, an expert image interpretation system, on the average performed worse than its users for diagnoses of focal bone lesions. This difference was only marginally significant for experienced residents at low false positive rates and not significant for inexperienced residents.

The implications of these results are that with the present RIIS system, an average user's performance would not be improved by help from the expert system. It should be noted that in some specific instances RIIS outperformed the user and in these instances RIIS might improve the user's performance.

The fact that RIIS was capable of better performance than inexperienced residents shows that RIIS could improve the performance of inexperienced users if an "accurate" description could be obtained from them. Performance of the RIIS system could also be improved by adjusting the knowledge base. The present knowledge base has several known inaccuracies which need to be corrected.

Future expert image interpretation systems need to account for variations in users ability to "accurately" describe the important findings. This could be accomplished by direct input of the image, modification of the expert system by experience level and user specific knowledge bases. If "accurate descriptions" could be obtained from inexperienced residents, RIIS would be capable of improving their performance in differential diagnosis of many focal bone lesions.

Note: "early stage d'ev. A "simplistic" system."

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Radiologic Knowledge Representation & Axis Display in the IMAGE/ICON System

Pradeep Mutalik, Paul Fisher and Henry Swett

Department of Diagnostic Radiology, Yale University School of Medicine, New Haven, CT

Introduction

Artificial intelligence in medicine is a field of research that has seen a fair amount of activity over the last twenty years. Computer-based expert systems have been designed in many domains of medicine. Yet very few of these systems are in routine clinical use. What is the reason for this almost universal rejection by the medical community? Are computer expert systems just not good enough? Obviously, this is not so, because systems such as Internist have been shown to perform at levels close to the best experts in the field (Miller et al, 1982). There must be some other factor that conventional expert systems lack. We believe that the missing factor is simply ease of use. Most expert systems have been created to prove the point that computers can capture expertise in restricted domains -- they were never designed to fit into the busy environment of the clinic. From one point of view, the focus of medical expert system designers on the representation and manipulation of medical knowledge was necessary, because that is a formidable task in itself. Now that some inroads have been made in that direction, however, it is time to design expert systems so that they address the problems of interfacing with busy physicians directly. This paper discusses some of the design considerations that have to be incorporated into an expert system from the outset if it is to become easy enough to use routinely in a clinical setting. This is based on our experiences in designing the IMAGE/ICON system which is a prototype expert system that provides both text as well as image output as an aid to radiologic differential diagnosis (Swett et al, 1989).

The domain of radiology itself presents a great challenge for expert system design. Traditional expert systems in medicine provide verbal material such as diagnostic criteria, lists of differential diagnosis, additional clinical or radiologic features to search for to better characterize an abnormality, or distinguishing features between several possible diagnostic candidates. Such verbal explanations can strengthen a physician's cognitive analysis of a case. In a visually oriented discipline like radiology, however, a great deal of reasoning occurs at a primarily visual or pattern recognition level. It is difficult for computers to help in this because optical pattern recognition by computer is still at a very rudimentary stage. A central design philosophy in our exploration of knowledge-based systems in radiology has been to

find ways for computers to complement human native intellectual skills by exploiting their unique ability to organize and recall information. In IMAGE/ICON therefore, we explore the possibility that a computer expert system might also select and display relevant images from a potentially large database of proven cases in a manner that would help radiologists to reason visually. In this paper we focus primarily on how we have attempted to achieve intelligent image retrieval in the IMAGE/ICON system.

In order to integrate intelligent image display smoothly into a reading room setting it is necessary to 1) Allow the radiologist to keep focus on the case at hand, yet anticipate his or her diagnostic needs; 2) Retrieve a set of images that meet those needs in a focussed way.

Anticipation of Radiologist's Diagnostic Needs

The idea that images can be useful to a radiologist is based on the recognition experience that most radiologists will find it very easy to identify with: "Oh, yes! I remember a case which had a lesion similar to this. This is obviously disease X". Sometimes this recognition experience is as clear-cut as described above. More often, however, the experience is somewhat more fuzzy: "I do recall that similar lesions are seen in diseases Y and Z. But the border of this lesion is somewhat unclear...". At such times the radiologist has to rely on imperfect human recall. If a computer system could, *at this very moment*, produce proven images of both the diseases in question comparison would be aided tremendously.

Two points should be noted about the above scenario. First, it is essential that the radiologist be allowed to focus on the case at hand. Typically, the radiologist would be dictating the case report for transcription. To have the radiologist take time out to describe the findings via lengthy keyboard interaction would be a distraction and waste precious time, thus making the value of any benefit of the expert system advise quite questionable. Secondly, the exact nature of the images that it might benefit a radiologist to see will vary depending on the specific intricacies of the problem domain as well as during different stages of the case analysis. A successful radiologic expert system must be able to deal with these problems.

The only solution to the first problem seems to be to combine the expert system with a computer-based reporting system. In that way all the information that is being described about the case would already be known to the expert system. This is easy enough to do in those few areas of radiology where check-off forms are used, as for example in mammography screening at some centers. Computer screens can easily be designed to mimic paper forms and can even improve substantially on them. IMAGE/ICON uses Apple Macintosh™ style dialog boxes and menus for entry of cases if this mode of entry is acceptable. In most areas of radiology, however, voice reporting is still extensively or almost exclusively used. We have interfaced IMAGE/ICON to a commercial radiology voice reporting system (VoiceRAD, developed by

Kurzweil Applied Intelligence Inc.) that uses a trigger-phrase lexicon to generate radiographic reports. This is very exciting because it allows IMAGE/ICON to work 'in the background' as the case report is being dictated, coming up with its text and image output whenever required, without the radiologist having to do anything different from what he or she normally does. The fact that the cases are dictated into the system using discrete trigger words and phrases, makes it easy to translate them both into the complete sentences needed in the report, as well as the 'tuple' representation required internally by the expert system. Thus, if the radiologist says "Mass small high density location sub-cutaneous", the voice system will enter the following sentences into the report: "There is a small high-density mass. The location of the mass is sub-cutaneous." At the same time, the case data is piped into IMAGE/ICON in the form of name-attribute-value tuples such as (mass present yes), (mass size small), (mass location subcutaneous), etc. After the radiologist has finished dictating the report, which includes the tentative diagnosis, he or she can say "Analyze". This signals the expert system to which come up with a text critique and a set of images relevant to the case. At this point, the radiologist can examine the critique and the images in detail, after which he has the option of changing his diagnosis before the final report is printed.

Voice recognition technology is improving steadily, and systems that can understand continuous speech may start becoming available a few years from now. These would undoubtedly provide the best possible expert system interfaces as they would truly allow most radiologists to report cases as usual, and get expert-system advice without any further effort. The integration of continuous speech with expert system advice would seem to require sophisticated natural language parsing in order to translate the report into the internal symbolic form required by the expert system. This problem might be alleviated by the fact that some syntactic parsing would already be done by the voice recognition system (this might be a *sine qua non* for continuous speech recognition), so that it would be possible to get some kind of processed output from the voice recognition box. Also our preliminary studies show that in constrained domains such as medical reporting it is possible to make sense of natural language text by judicious search for keywords plus identifying all possible expressions that signify negatives.

The second aspect of getting an expert system to fit into the reading room environment is to anticipate what images would be most useful to the radiologist at different stages of the diagnostic process. As mentioned above, these would differ from domain to domain and require critical study of the area in question. In the area of mammography (one of the domains for which an IMAGE/ICON module has been designed) these are some of the questions that the radiologist has to wrestle with:

- 1) Is this film technically well done? Do I need a repeat?
- 2) Would a different view or a compression view be useful in this case?
- 3) Is this a lesion or merely a normal variant?
- 4) Is the difference between the current examination and the previous one significant?

- 5) I think this is entity X. Does entity X cause findings similar to what I am seeing?
- 6) What is the range of appearances of entity X?
- 7) What are all the benign things that resemble this finding?
- 8) What are all the malignant things that resemble this finding?

The list is obviously incomplete. In most cases the answer to most of these questions would be obvious. But when it is not, looking at a group of images that illustrate the point in question could be a great help. In IMAGE/ICON we have tried to this by using the Axis display.

Axis Display

The basic unit of image display in IMAGE/ICON is the image axis. An axis consists of groups of images that are similar in well-defined ways, and that are ordered according to well-defined criteria. From the user's point of view, an axis is nothing but a set of images that provide a focussed answer (in the form of images of proven cases) to a specific spontaneous query. Thus, in the case of query 3 above, it would be helpful to see a group of images that presents a range of normal variants that can be confused with a given finding, followed by images showing actual examples of the troublesome finding ordered from most subtle to most obvious. It would then be much easier to call the finding one way or the other.

An important aspect of an image axis is that the key features of the similarity are generalized from the case at hand. Thus if a mass is described as a finding in the current case, the above example would show subtle examples of masses; if a cluster of microcalcifications is described as the finding in another case, subtle examples of clustered microcalcifications would be shown in the same axis.

An example of the axis display is shown in figure 1. Each of the 5 horizontal rows of small images on the right side of the screen represents a single axis. The first panel gives the title of the axis, and the number of images it contains. This is followed by the images themselves, ordered in whatever manner is adequate for that particular axis. The axis images can be scrolled laterally in order to examine the whole axis. Also, if any of the small images is found to be similar to the case at hand, clicking on it with the mouse enables the user to examine it at full resolution.

In order to dynamically generate such axes, it is necessary for the system to know exactly what each image contains. For this purpose, we have developed a prototype image description language. Information about every image is stored in the form of a coded database of findings. Every finding on the radiograph is assigned its own set of unique descriptors that can take on different values and are associated with scalars. Thus "size of mass" would be a field-descriptor for a mass which would contain a numeric value representing the size of a mass. Similarly, one field descriptor for a calcification would be "type of clustering", where the value could be localized or diffuse. Every sub-finding of a finding can be represented (when warranted)

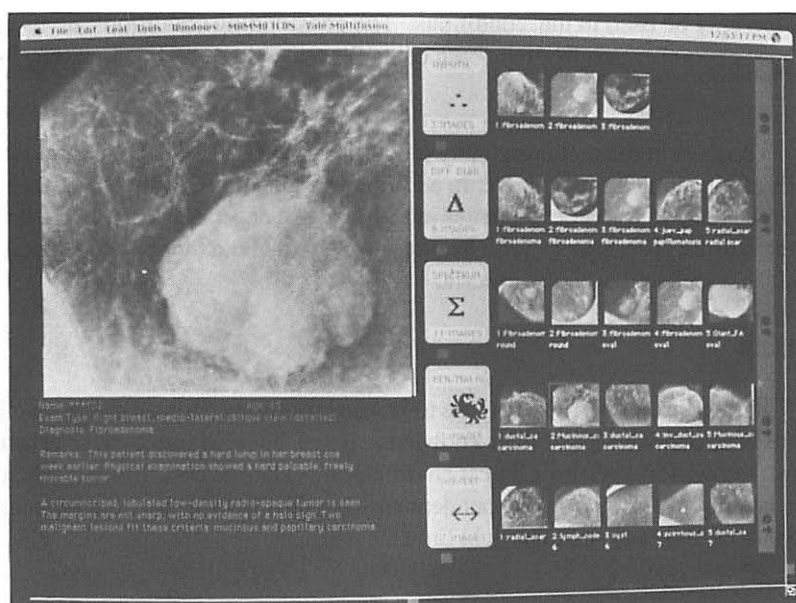


Figure 1. Axis Display

as a finding itself, defining its own specific descriptors. Thus, if in a certain radiograph it is thought that the border of a mass should be described in very great detail, that can be assigned the status of a finding in its own right.

The field descriptors cover various different aspects of a finding including size, shape, location, type, typicality, conspicuousness, geographical and etiological relationship to associated findings, dynamic temporal behavior, spatial extent in other views, etc., in addition to descriptors unique to the finding.

Every finding attribute field includes a 5-point scalar which gives the degree or intensity of whatever scale can be naturally applied to the attribute in question. The scalar means different things for different finding attributes. For example, to describe the shape homogeneity of microcalcifications the scale would go from 1 for inhomogeneous (having very different shapes) to 5 for extremely homogeneous (all having similar shapes). On the other hand for temporal behavior involving mass growth, 1 would mean very slow growing and 5 would mean very rapidly growing. The inclusion of such a scalar enables the coding of extremely precise information, which is required for very sophisticated querying of the image database, that is specifically used in axis-based retrieval.

Internally in IMAGE/ICON, an axis consists of a Boolean set of prioritized conditions that constrain a search, and another set of prioritized conditions that organize and order the images found in the search. Any of the fields in the image

description may be used in the conditions. The constraining conditions are usually derived by generalization from the case being described currently so that they are relevant.

The axes in the mammography module of IMAGE/ICON are derived from the kinds of questions shown above. In addition two general purpose axes are: 1) The Best-match Axis, which orders images in the database depending on how well they match the current case; and 2) The User-defined Axis, where the user can specify appropriate search and ordering criteria.

Conclusion

If medical expert systems are to be used routinely, considerable care has to go not only into the design of their knowledge bases, but also into their interfaces and into how they will fit into the clinical environment. The success of medical expert systems is not only going to be dependent on what they have to say, but how they say it and whether they say it at the right time.

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Towards a 3-D Medical Image Analysis System Based on a Continuous Modelling

M. S. M. Marqué, S. Lavalée, C. Goret-Lezy and P. Cinquin

Laboratoire d'Informatique Médicale, Faculté de Médecine,
La Tronche, FRANCE

Univ Grenoble, FR.

Summary

This paper deals with continuous modelling for 3D medical image analysis. This reconstruction method is initially more complex to implement than the Cuberille method but it takes advantage of algorithmic geometry technics which provide powerful means for 3D image processing. High quality 3D image rendering is performed and a new 3D boundary tracking method based on differential properties has been developed.

1 INTRODUCTION

3D images are widely used in medical imaging. They are generally constructed from parallel serial section images obtained from Computed Tomography or Magnetic Resonance Imaging.

Our aim is to provide the clinician with new computer graphic tools which help him in three-dimensional image analysis for diagnostic and therapeutic purposes. A 3D medical image analysis system has to suit some of the following specifications :

- to improve the understanding of the shapes of the studied objects and then to help a surgical planning,
- to enable to quantify the object by morphological parameters such as the volume,
- to be able to compare the images produced by various imaging systems (CT, MRI, X-ray pictures...) and to match these multimodality information,
- to perform an accurate estimation of the relative position of objects. That point is essential to guide a surgical intervention, for instance when introducing a needle into the brain or when focusing radiotherapy.

This paper presents our choices to perform this analysis system and our current developments. In each section the state of the art in the concerned area will first be presented.

2 VOLUME MODELLING

In most present 3D imaging applications, the 3D scene is represented by a 3D array of volume elements named voxels. This "Cuberille" modelling [HER 88] requires either an isotropic resolution of initial data (and then many slices) or to compute intermediate slices (by interpolating the original cross-sections for instance). Moreover, volume rendering sometimes needs to compute surface gradients which have to be approximated [HOH 86].

The continuous modelling allows to get around these problems. Instead of using discrete elements to model data, we use 3D continuous elements which are made of tri-cubic B-spline functions. Thus the density f is defined in every point (x,y,z) of the

volume and is written as:

$$f(x,y,z) = \sum \alpha_{ijk} * B(x-i) * B(y-j) * B(z-k) \quad (\text{Eq. 1})$$

where B is the basis B-spline function:

$$B(t) = t^3_+ - 4 * (t - \frac{1}{4})^3_+ + 6 * (t - \frac{1}{2})^3_+ - 4 * (t - \frac{3}{4})^3_+$$

We note : $Y_+ = Y$ if $Y > 0$

0 else where

This density function f has to approximate the initial slices. This 3D approximation problem is easily solved because it can be broken up into 3 one-dimensional problems. We chose to smooth the initial data in each slice and to interpolate between slices [CIN 87]. The major advantage of this model is to allow the computation of density and its derivatives anywhere in the volume. Thus ray-tracing volume rendering is available for a low number of slices (often corresponding to the clinical use) and provides better quality images achieving maximum sharpness without introducing discontinuities. Another application is to compute new slices in others planes than the set of initial slices. Satisfactory results are even obtained with a limited number of slices. (Fig. 2,4b)

Major areas of application are cranial and skeletal imaging (Fig 1). 3D visualization helps the surgeon to perform a surgical planning: the aim is for instance to determine the presence and extent of congenital or acquired, craniofacial or orthopedic deformities. Efficient and reliable results have been obtained in clinical use. Another area of application is Computed Assisted Stereotaxy [LAV 89] where the surgeon can select the optimal trajectory to introduce a needle into the brain (Fig. 2).

3 3D BOUNDARY DETECTION

The previously presented method makes it possible to display a surface which is not modelled. Object manipulation and quantization require an analytical knowledge of the object surface. Thus, the first step to be achieved is segmentation. The huge size of data makes algorithmic complexity and storage requirements the key points of 3D edge detection.

3.1 State of the art:

The classical approach consists in computing the gradient by applying an operator which enhances discontinuities. Most of all these operators are 3D generalization of 2D edge detectors [MOR 81]: Roberts [LIU 77], Hueckel [ZUC 81], Canny [MON 89], Marr and Hildreth operators [HOH 88]. Critical problems of many of these detectors concerns the size of the convolution mask, edge points linking, gap filling and false edge points eliminating.

A possible solution is to use "snakes" [KAS 87, AYA 89] but up to now their extension to the 3D case raises specific problems.

Through cuberille modelling many surface tracking algorithms have been developped ranging from a simple thresholding to a cost function [HER 88, GOR 89, CAP 89]. But these technics are very sensitive to inter-slice distance.

3.2 Methodology:

The continuous modelling allows stable evaluation of differential operators such as gradient or laplacian. However, tracking the surface of an object can be proved to be equivalent to finding a stable invariant manifold of a system of differential equations.

Finding this manifold turns out to be a particular case of surface intersection problems [PHI 84] which provides an immediate analytical representation of the surface.

The other major advantages of this method are to perform segmentation and surface tracking simultaneously, to describe complex structures in which branching problems can occur, and to provide accurate and reliable results.

Let us first consider the 2D problem. We are looking for a boundary surrounding an object with an approximatively homogenous density f , thus verifying:

$$f(x,y) = \text{constant} \quad (\text{Eq. 2})$$

This curve is represented with parametric coordinates by :

$$x = x(t); y = y(t)$$

The continuous modelling involves first derivative existence of f ; then a solution should verify the following equation 3 obtained by differentiation of (2):

$$x'(t) * \frac{\partial f}{\partial x} + y'(t) * \frac{\partial f}{\partial y} = 0 \quad (\text{Eq. 3})$$

A particular solution of (3) is :

$$\begin{aligned} x'(t) &= \frac{\partial f}{\partial y} \\ y'(t) &= - \frac{\partial f}{\partial x} \end{aligned} \quad (\text{Eq. 4})$$

But this system does not provide a stable solution: a perturbation (due to noise) which would move the curve away from the level line could not be corrected. That is why we add a component to the system (4) which brings the curve back to the level curve " $f(x,y)=\text{constant}$ " according to the greatest slope line of the $(f-\text{constant})^2$ function. We thus obtain:

$$x'(t) = \frac{\partial f}{\partial y} - \beta * \frac{\partial f}{\partial x} * (f - \text{constant}) / Gf \quad (\text{Eq. 5})$$

$$y'(t) = - \frac{\partial f}{\partial x} - \beta * \frac{\partial f}{\partial y} * (f - \text{constant}) / Gf$$

$$\text{where } Gf = \frac{\partial f}{\partial x} * \frac{\partial f}{\partial x} + \frac{\partial f}{\partial y} * \frac{\partial f}{\partial y}$$

This system consists of two parts: the first one corresponds to "edge tracking" component and the second one is a kind of "elastic force" which allows noisy image processing. The β parameter allows to balance these two terms. The system (5) may be solved by numeric analysis methods with initial conditions. The parametric representation of the curve is straightforwardly obtained. Let us remark that this differential system may be built in any plane of the 3D volume.

Particular points of the object surface such as local extrema can be found by similar methods [MAR 89].

3.3 3D Strategy:

We are looking for a surface verifying $f(x,y,z) = \text{constant}$

The data geometry has induced our parametrization of the surface we are looking for :

$$x = x(t,h); y = y(t,h); z = z(h).$$

Our boundary tracking method is as follows:

The algorithm starts with a point of the surface and with a characteristic density value. For each k slice, the differential system is solved in order to obtain a closed curve. From some points of this curve, we follow the object surface until the next $(k+1)$ slice by building new 2D differential systems in slice-perpendicular planes. The ends of these curves belong to the $(k+1)$ slice and are thus used as starting points to find one or several contours on this slice. Such a search is also performed towards previous slices: all object components can then be found. It is already an error recovery mechanism because links previously found between contours are verified in the same time.

The algorithm stops when all slices have been processed or when the object surface has been entirely described.

Other segmentation control process are based on global statistical or geometric properties. They use simple data such as density, gradient along the contour or the curve segment, surface, length and allow to correct some errors due to noise. These control processes are general enough to be applied to all cases. More specific a-priori knowledge might be introduced at this level to improve segmentation control for particular objects (convexity for instance, number of branches,...).

This algorithm was tested on CT (Fig 3) and MRI images (Fig 4).

Homogeneity is not always a stable characteristic of an anatomical structure. Now we are working on differential system building which performs $H(f) = 0$, where $H(f)$ is an operator as the laplacian or Marr-Hildreth detector. A possible extension of our method is to include a model of the object of interest. This model is described with spline functions and will be iteratively modified to fit with the real object.

4 SURFACE MODELLING

4.1 State of the art:

Segmentation step usually provides a set of contours. A surface modelling based on these contours is needed to allow shaded surface display. A solution is to create intermediate contours by dynamic elastic interpolation (LIN 88) and to display the surface on a Voxel Processor. Triangulation techniques have been applied to compute contour interpolation (FUC 77, BOI 88). But branching description sometimes requires user-driven interaction.

4.2 Our Method:

In our case, this problem is solved at the segmentation level. Our algorithm allows to automatically find all object components and to link them together (see § 3.3). The information brought by the segmentation step allows to easily model the surface with surface patches by means of the set of contours and paths linking them together. Thus, this technique achieves branching description without any user-driven interaction.

4.3 Applications:

Shaded surface display, simple object manipulation (like rotation) and quantization use classical algorithms on surfaces defined by their parametric representation.

Now work is in progress to apply the presented continuous modelling to surgical planning and to matching of multi-modality information. For instance, in Computer Assisted Neurosurgery, the surgeon needs to match intra-operative 3D images (from CT or MRI) with per-operative X-ray pictures [LAV 89 & 90]. We suggest to use only reference 3D internal anatomical structures (the ventricular system) : an iterative 3D/2D matching algorithm on segmented surfaces is performed. Thus the surgeon's strategy, chosen on 3D images, to reach the target (a tumour for instance) is correlated with intra-operative information.

5 CONCLUSION

Some objectives of a 3D medical analysis system such as visualization, manipulation and quantization of 3D internal structures of patients have been achieved. This "basic tool" is going to allow further specific developments in Computer Assisted Medical Interventions (CAMI) (see [MUR 90] for a review of existing applications and of work under development).

Work in progress also concerns improvement of the 3D segmentation step in order to include an anatomical model of the object of interest. We named this approach "spline snakes" because of snake similarity. The major advantages are as follows: the model is described by a limited number of control vertices and a 3D extension is possible easilier.

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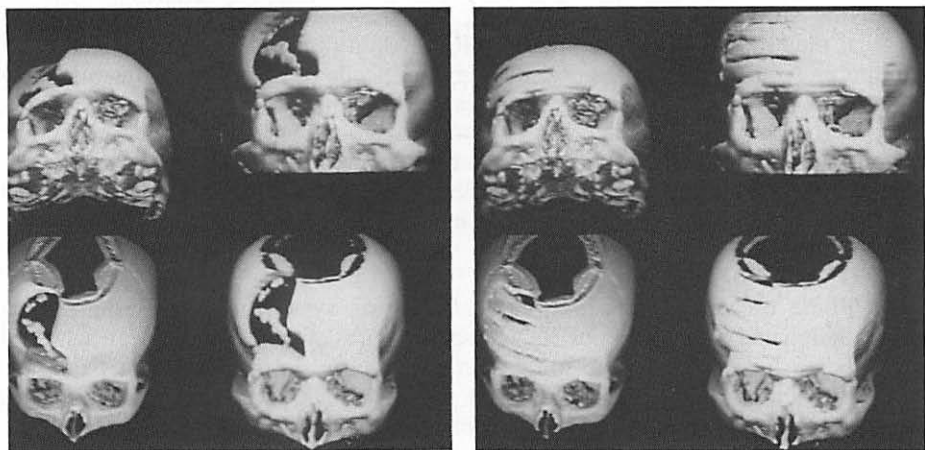


Fig. 1 : 3D display of the skull reconstructed from Computed Tomography images before (left) and after (right) operation.

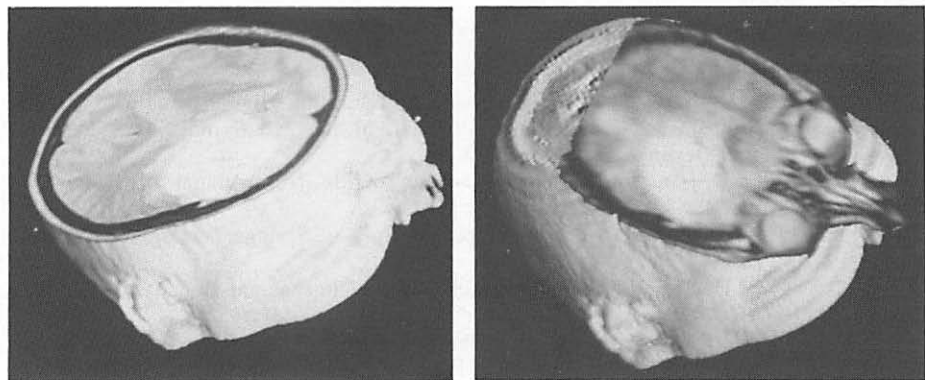


Fig. 2 : Interactive selection of a target and a trajectory on MR images. Reconstructed oblique sections are superimposed on a 3D display of the head (obtained by processing 20 MRI slices)

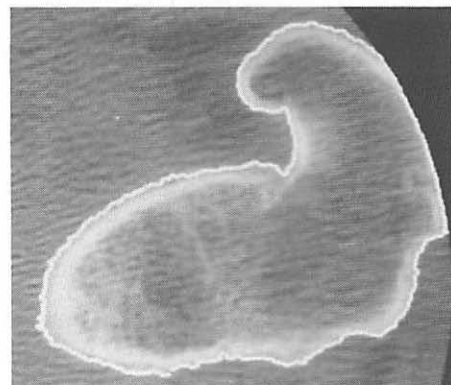


Figure 3 : Segmentation of a CT image of a femour

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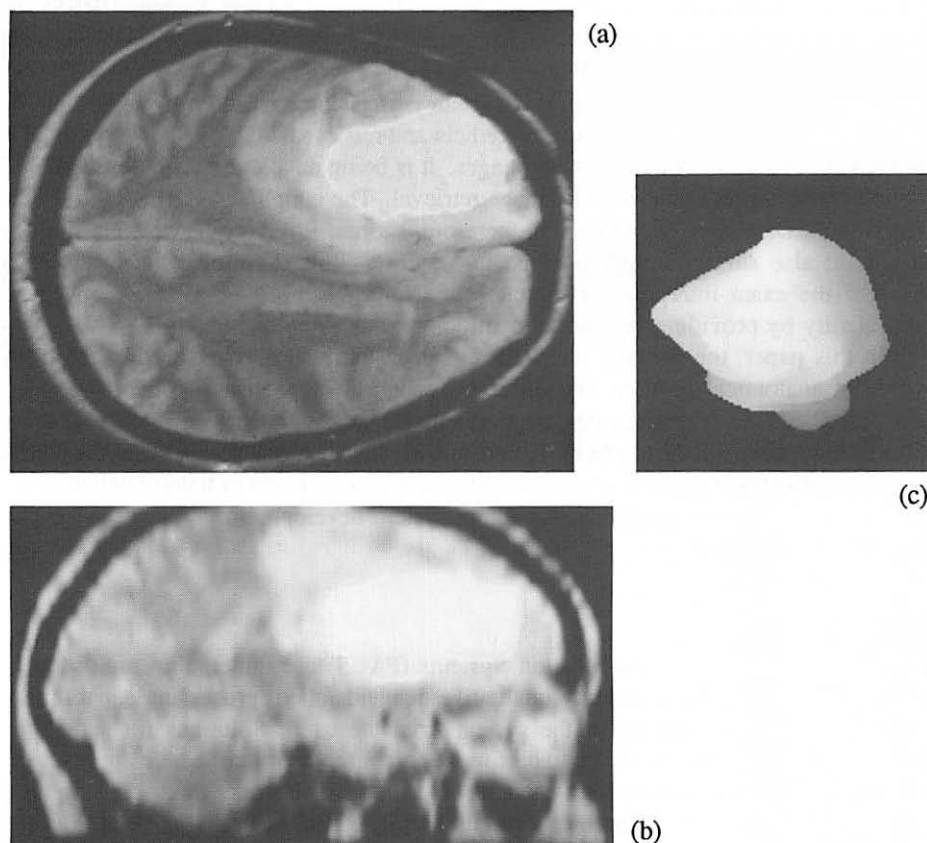


Fig. 4: Results of a tumour segmentation (MRI)

(a) edge detection of the central part of the tumour

(b) segmentation in a plane perpendicular to the initial slices

(c) 3D display

Image Retrieval Expert System

Huichin Wang, Olivia R. Liu Sheng and Hong-Mei Chen Garcia

Department of Management Information Systems,
College of Business and Public Administration,
University of Arizona, Tucson, AZ

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grad students

Theron W. Ovitt, M.D.

Department of Radiology, College of Medicine,
University of Arizona, Tucson, AZ

sup. in Toshiba Corp., Japan.

Uof A is pioneer in developing this technology

Abstract

A prototype knowledge-based system, Image Retrieval Expert System (IRES), is being developed at the University of Arizona. This system is to be coupled with the distributed database system of Picture Archive and Communication Systems (PACS) to achieve high speed image retrieval system performance required by radiologists.

IRES is an automated tool which predicts and retrieves "old" images required for immediate comparison with present images. It is being developed through the use of radiologists' expert knowledge in image retrieval. The coupling of IRES with PACS Distributed Database (DDB) should, therefore, shorten PACS system response time. It should also save radiologists' time in selecting films, minimize the turnaround time of the exam interpretation function and improve the diagnostic effectiveness and quality by providing relevant and sufficient images automatically.

In this paper, the demand for IRES to select "old" and "relevant" images from different anatomical portions and different modalities as well as the heuristic rules are described. As heuristic rules are implicit and experts are less available, special efforts have been made to obtain expert knowledge. The development of the IRES prototype illustrates the new application of expert system in the radiology department. Moreover, it provides guidelines for future system development.

1 Introduction

Picture Archive and Communication Systems (PACS) are undergoing rapid development to cope with increasingly qualitative demands about processing capabilities, efficiency, and the capacity of the system from the user. Solutions for satisfying these demands may be divided into hardware, software, and intermediate approaches. Hardware solutions include high-capacity fiber-optical networks, high capacity/fast data storage systems [1], special workstations [5], etc. Distributed database design is an example of an intermediate approach [3]. We herein propose software approach, an expert system for image retrieval named Image Retrieval Expert System (IRES). It is designed to better meet the response time requirement of image retrieval, considering a reasonable cost/performance tradeoff.

The basic idea and functions of IRES were conceived following careful observations of radiologists' exam interpretation (reading) activity for the requirement analysis of PACS. Retrieval of old images is necessary when radiologists need to compare a newly taken exam with "old exams" of the patient undergoing diagnosis. Currently, film librarians retrieve the whole file of images of the patient and put the most recent related images taken by the same modality for the same anatomical portion onto the viewbox, or alternator, etc. Radiologists compare images on the viewboxes while occasionally fumbling through the remaining images in the film jackets for related images in a matter of a few seconds. In order for PACS to equal the performance for "old" image retrieval of the current manual film-based system, a software system needs to carry out at least two tasks achieved by film librarians and radiologists. First, because a single image takes several megabits and the amount of images in a hospital is large, a multilevel data storage system is proposed by placing "older" images in less accessible and slower storage devices to minimize the cost [4]. To reduce system response time in this design, a means is to be devised to pre-fetch relevant images to local buffer memory. Second, because not all "old" images are necessary in the film interpretation task and the local buffer memory is limited, detailed rules used by radiologists to select "relevant" images should be identified and automated. Considering these functions, we propose IRES should pre-fetch images to local buffer memory using a set of heuristics rules acquired from expert radiologists.

Like any other expert system (ES), the development of IRES has to go through an iterative design life cycle including knowledge acquisition (KA), knowledge analysis/representation, implementation tool selection, prototyping, testing and installation [6]. Among these phases, KA involves two groups of people, knowledge engineers and experts, and determines the system usability and performance which depend on the accuracy of knowledge acquired from radiologists. Therefore, methodologies, activities, assumptions, and results derived in KA will be accounted first. The architecture of the IRES prototype will be described. The advantages of IRES and its impact on PACS performance will be addressed. Finally, the achievements in the efforts for building the IRES prototype are presented and future works to be done are addressed.

2 Knowledge Acquisition

The development of the IRES prototype started with knowledge acquisition. Knowledge engineers first collected information from the domain environment to achieve a general understanding of the internal process of the domain and then generated some assumptions. Those assumptions were verified with experts. Two methods, interviews and GDSS sessions, were used to acquire the correct knowledge from single and multiple experts respectively. This section describes important activities in the knowledge engineers' efforts to elicit heuristic rules and the results from that process.

2.1 Initiation of the IRES Prototype

Through site observations, knowledge engineers learned the processes and data flow of the radiological exam interpretation function. In the current manual system, radiologists are scheduled to interpret radiological exams. As mentioned in the introduction, film librarians prepare and retrieve images to be read. The retrieval activity is "routine" because the whole film jacket of images are retrieved for each patient who takes new exams. Yet, partly due to the limited space on viewboxes or other viewing consoles, only the most recent relevant exam is posted. Radiologists occasionally select images from the patient's film jacket to better achieve diagnosis task.

Our site observations of the exam interpretation function allowed us to conceive several important criteria for retrieving images. They are described later along with the observations from which the assumed retrieval criteria are derived. They include 1) patient name - images of the same patient are compared; 2) age - age is on the consultation requisition form (CRF) which is attached with the newly taken exam; 3) sex - sex is found on the CRF; 4) section - section is on the CRF; 5) current disease - suspected disease is on the CRF; 6) medical history - medical history is retrieved along with the old exam; 7) modality - images taken of the same modality are usually compared; 8) anatomical portion (AP) - images for the same AP are compared most frequently; 9) procedure number - procedure number has direct co-relation with AP; 10) age of films - recent images are most frequently retrieved.

We also observed that under different hospital scenarios/activities, the retrieval criteria may change. The different hospital scenarios include emergency, surgery, conference, inpatient diagnosis, and outpatient diagnosis.

Additionally, we made use of the statistical results of a survey conducted in March 1989. Having become aware of retrieval criteria, various scenarios for image retrieval, we continued our efforts to explore and verify the exact "rules" for image retrieval employed by radiologists by means of interviews and GDSS sessions.

2.2 Knowledge Acquisition Methodologies

Interviews and GDSS sessions are techniques used to verify the observed image retrieval criteria and explore new ones. The interview is a traditional approach for acquiring specialized domain knowledge from experts. It is also time-consuming. On the one hand, knowledge engineers have to spend time arranging appointments for initial or follow-up interviews, preparing/designing questions, recording discussions, analyzing interview results, etc. On the other hand, domain experts have to spend time meeting and understanding what knowledge engineers want to know. Generally speaking, only one expert participates in an interview.

Two types of questions were asked in interviews. The first type aimed to clarify and verify the assumptions about image retrieval criteria and scenarios derived from our general observations. The second type focused on cases which represented the specialty of the expert being interviewed because radiologists usually specialize in one area.

In the interviews using the first type of questions, we asked engineers to comment

on the relative importance of each retrieval criteria and to describe image retrieval activities in each scenario. In the interviews using the second type of questions, we first decided cases to be studied based on the specialty of available experts. We were concerned with cases involving multiple-modality retrieval, cross-anatomical portion retrieval, or selection of exams from a large amount of relevant images. Four target areas were chosen, namely pediatric cases in cardiology, surgery in cardiology/orthopedics, and chronic cardiology disease. The experts further narrowed the scope by concentrating on congenital heart defects for pediatric cases in cardiology, coronary heart disease for chronic cardiology disease and other surgery related cases.

A Group Decision Support System (GDSS) at the Department of Management Information Systems at the U of A was utilized to verify and obtain knowledge from multiple experts simultaneously. GDSS provides an electronic form of communication between knowledge engineers and experts as well as among experts. Domain knowledge is obtained from multiple experts and organized using GDSS facilities. Additionally, conflicting knowledge can be reconciled by immediate discussion at GDSS sessions using GDSS tools.

It takes a great deal of preparation to effectively use GDSS sessions in knowledge acquisition. Knowledge engineers have to coordinate GDSS sessions, invite experts, contact the GDSS facilitator, prepare GDSS session agenda/questions, and arrange follow-up GDSS sessions or interviews, etc. As this writing, one GDSS session had been held with the coordination and assistance from the management of the Radiology department at University Medical Center (UMC). Since each physician attending the session had his own specialty, questions asked in this GDSS session aimed at having physicians brainstorm on general cases and reconcile any conflicts that arose. Due to this dynamic brainstorming process and the participation of multiple experts, the amount of knowledge acquired in one hour is much more than that acquired in a one-hour interview. Group meetings can spare knowledge engineers from conducting repetitive procedures in KA and ensure the accuracy and consistency of acquired knowledge immediately.

2.3 Results from Knowledge Acquisition

In the interviews seeking to assure the validity of assumed retrieval criteria, it was found that almost all of the conceived image retrieval criteria were relevant, but some corrections and additions needed to be made. Sex has no significant relationship with image retrieval. However, different disease types, such as acute and chronic, will result in varied retrieval patterns. It was also found that not all of the scenarios required image pre-fetching, one of the primary functions of IRES. **The contribution of IRES will only be found important in those scenarios in which image retrieval is routine (as opposed to ad hoc in conference scenario), such as cases of surgery preparation, inpatient/outpatient diagnosis, etc.** In the interviews concentrating on selected cases, heuristics rules are obtained pertaining to them. For example, in our study in cardiology, we found that CT was never used for cardiology cases. The GDSS session allowed us to obtain more accurate and varied rules due to the different backgrounds of participants.

3 IRES Prototype

Based on the results obtained from KA sessions, an IRES prototype was developed to quickly obtain feedback from radiology experts, evaluate ES tool and specify the performance criteria for IRES. Connections between a knowledge-based system (KBS) and a database system (DBS) fall into three categories, system enhancement, KBS and DBS coupling, and integration of KBS and DBS. Among them, KBS and DBS coupling is perceived as a suitable architecture because both IRES and PACS are kept intact and independent, yet interrelated. The IRES prototype involves three major components, the databases, the procedural control algorithm, and the rule base. The declarative knowledge in the databases and procedural knowledge within the rule base constitute the knowledge base of IRES. The databases are managed by a DBMS and can be accessed by ES. The rule base consists of 44 heuristics rules of image retrieval presented by the production system. The procedural control algorithm imposes an external control over the activation of rules. Currently, EXSYS was chosen as the expert system tool to implement the components. We assumed that the connecting DBMS would be responsible for retrieving information from the databases according to the specifications generated by the IRES prototype. An interface, a text file, is used to achieve this communication. It should be noted that the operation of the system is invoked in batch and no interactive consultation is supported.

4 Advantages of IRES

IRES is designed to overcome the bottleneck in system performance caused by the large amount of data in a hospital context, as well as the large amount of memory space required by each image. Hence, by introducing IRES, image transmission can be expedited by pre-fetching relevant images at off-peak time periods and the amount of images to be transferred can also be reduced with selective retrieval rules. Thus, the response time can be greatly improved. Due to the improvement in performance, the exam interpretation activity involving IRES can be expedited.

IRES also provides the valuable advantages of most expert systems. With the use of knowledge acquisition methodologies, knowledge engineers acquired implicit and ill-structured domain knowledge from experts and organized the knowledge into a form suitable for the use of an automated system. The organized knowledge, then, can be preserved regardless of the absence of experts. Given the ability to preserve knowledge, explain results, ES serves as a training tool for novices in the domain area. The advantage is important because the accumulation of past experiences and education is necessary to refine the state of the art techniques in this particular medical field.

5 Achievements and Future Works

IRES is needed to improve the performance of a PACS to meet the radiologists' response time requirements. Although the IRES prototype is simple for the moment, it landmarks several significant achievements in this research. The IRES prototype allows us 1) to verify the assumptions of image retrieval criteria under different scenarios; 2) to compare and identify effective knowledge acquisition methods; 3) to experiment the encoding of heuristic rules; 4) to engage experts in the process of IRES development; 5) to estimate the future work needed and outline a detailed design for a complete IRES.

One of the contribution of the IRES prototype is to obtain quick feedback from the user. Feedback can be obtained by displaying demos followed by interviews or questionnaires with individual experts, general group discussion using GDSS tools, or panel discussion in each section. To improve the effects of testing, better explanation and learning capabilities should be incorporated in the system so that the user is allowed to employ, understand, and comment on the system behavior. Moreover, the user may input new rules in the direct interaction with the system. The learning capabilities of the system should be so powerful that experts only need to input new knowledge in a form similar to that of natural language or spreadsheets/databases without worrying about the embedded formal knowledge representation.

Much work needs to be done to expand the current IRES prototype. More image retrieval criteria are to be acquired. A GDSS session will be of more use as the efficiency of the process and the accuracy of the knowledge are better achieved. More cases, especially complicated cases such as tumor, cancer, and heart transplant, need to be studied. Furthermore, we propose to adopt a look-ahead two-stage database access scheme to reduce the frequency of image access. In this scheme, IRES will first issue queries to surrogate files to decide whether the image requested are available. Once the response is positive, IRES issues formal queries to image files through an interface to DBMS. While one of the aim of IRES is to reduce the amount of images being retrieved with selective rules, temporal information should be recorded and help provide effective functions in selecting samples from a large number of images taken during a time span. Additionally, an interface, Workstation Queue Manager, is to be devised to decide at which workstation to put the retrieved images when multiple workstations are envisioned in future PACS.

Several tasks need to be done to achieve the proposed connection between KBS and DBS. It was also determined IRES is to be connected to a SQL-based DBMS, Sybase. A set of investigations on Sybase are to be conducted. A proper site for IRES, which is regarded as an independent system, is to be determined and other expert system shells which can be linked with Sybase should be studied. While considering the linkage with a distributed database management system, IRES should intelligently help avoid bottlenecks in data migration by accessing data about image location and decide when and where images should be efficiently retrieved [2].

In sum, it is believed that more research efforts are required to make IRES functional and useful in PACS.

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Interactive Object Dissection Using an Arbitrary Volume Mask

S.R. Arridge and A.D. Linney

Department of Medical Physics and Bio Engineering,
University College London, London, ENGLAND

Abstract

Many software and hardware systems exist to produce realistic images of 3D medical objects. The images they present are becoming familiar to the clinical community. With this familiarity comes a demand for more sophisticated facilities. The ability to satisfy these demands depends in part on the data representation employed. In particular, the ability to cut away parts of an object and look inside requires a volume representation, and ideally one retaining the grey level resolution of the original data. In many systems such cutting away is achieved by specifying a number of half-space clipping planes that intersect the data. Such techniques are limited in the volumes of interest (VOIs) that they can isolate. The requirements for Computer Simulated Surgery (CSS) include the isolation of arbitrarily complex VOIs, and the manipulation and visualisation of multiple objects simultaneously.

The UCL3D system uses a combination of greyscale data and volume masks. A number of facilities are presented that operate on Boolean expressions of objects and masks. Thus expressions can be visualised, translated, rotated, and merged. A combination of these facilities allows an interactive CSS system to be developed. Results applied to facial surgery are shown.

1 Introduction

Computer Simulated Surgery (CSS) is becoming recognised as an important application of 3D medical imaging systems [Hemmy 1983, Vannier 1983, Cutting 1986, Tessier 1986, Udupa 1986]. From a Computer Scientist's point of view the requirements may be summarised as data acquisition, preprocessing, segmentation, visualisation, manipulation, quantification, and registration. The first four of these elements have received considerable attention. Manipulation is the main feature discussed in this paper.

A question of interest is the appropriate representation. Early systems performed a static segmentation (thresholding, surface tracking, region growing etc.) to produce a binary object that could then be rendered (displayed) on a 2D computer screen. More recently dynamic segmentation techniques have developed that perform a

decision per voxel during the display algorithm, or else produce a "fuzzy" display by volumetric integration [Heffernan 1985, Levoy 1988, Troussel 1988].

When objects are to be "dissected" and manipulated, such fuzzy techniques would appear to be inappropriate, since an object needs to be unambiguously defined before it can be transformed. However, the approach outlined here is to dissect objects by defining a volume mask, or Volume of Interest (VOI) that is simply a binary partition of the data space. Subsequent operations are carried out on an expression (e.g. a Boolean expression) of the mask and the original data set. This allows a flexible surgical simulation environment to be developed.

Figure 1 shows an overview of the system that has been implemented. The rest of this paper will outline the means of mask generation and expression evaluation, with some examples from maxillo-facial surgical planning.

2 Volume Mask Generation

In the Surgical Simulation application, the user most often wishes to view a dataset and interactively demarcate sections to be modified. Thus it is useful to draw the required dissection and observe it in multiple views, editing as required. The process starts with the object Q and displays it in a number of views to obtain a set of displayed images $\{Dy_i\}$. For each view a number of arbitrarily complex *regions* $\{R_i\}$ are drawn on these images, where each R_i may have separately connected areas. Then the inverse projections are derived to form a cylindrical volume (CV) and an iterative method of forming the VOI is allowed by considering at any stage the partial intersection set :

$$(VOI)_k = CV_1 \cap CV_2 \cap \dots \cap CV_k \quad (1)$$

and creating each subsequent display as one of

$$Dy_{k+1} = \text{Display}(Q) \text{ under transform } T_{k+1} \quad (2a)$$

$$Dy_{k+1} = \text{Display_Boolean}(Q \cap VOI_k) \text{ under transform } T_{k+1} \quad (2b)$$

$$Dy_{k+1} = \text{Display_Boolean}(Q - VOI_k) \text{ under transform } T_{k+1} \quad (2c)$$

Thus some flexibility is allowed in creating the VOI. The basic philosophy is to use as many images obtained by equation (2) as are useful to provide the visual cues for creating the VOI.

The actual CV_i 's are intermediate and of no interest. Instead the VOI is built by editing the volume described by equation (1) at each stage.

3 Expression Evaluation

In the current system the data and masks are both stored in a hierarchical octree representation, the former as grey scale and the latter as binary. The purpose of this mask is to allow operations on the original data, inside or outside the volume

These are algorithms operating on pairs of trees, related by one of the Boolean operators Intersect, Union, Difference. Usually one of the operand trees is a binary VOI, and the other either a binary or grey data tree (Arridge 1989).

Explicit Boolean operations are required actually to create merged and split objects. The implementation of Boolean algorithms amounts to the evaluation of a simple rule set at each node. The rules for the three simple Boolean operations shown in Figure 2 where P/E is written because the intersection or difference of two Partial nodes might give an Empty node, (but not a Full node), and P/F indicates that the Union of two Partial nodes might give a Full node (but not an Empty one).

4 Examples

Patient 1, aged 15, was diagnosed as Crouzon's Syndrome (craniofacial dysotosis). The surgical procedure adopted is the *Kufner* osteotomy. It is a cut taking in the lower orbits of the eyes, to separate the maxilla. This whole piece is then advanced forward along the occlusal plane to correct the open bite. For this patient the

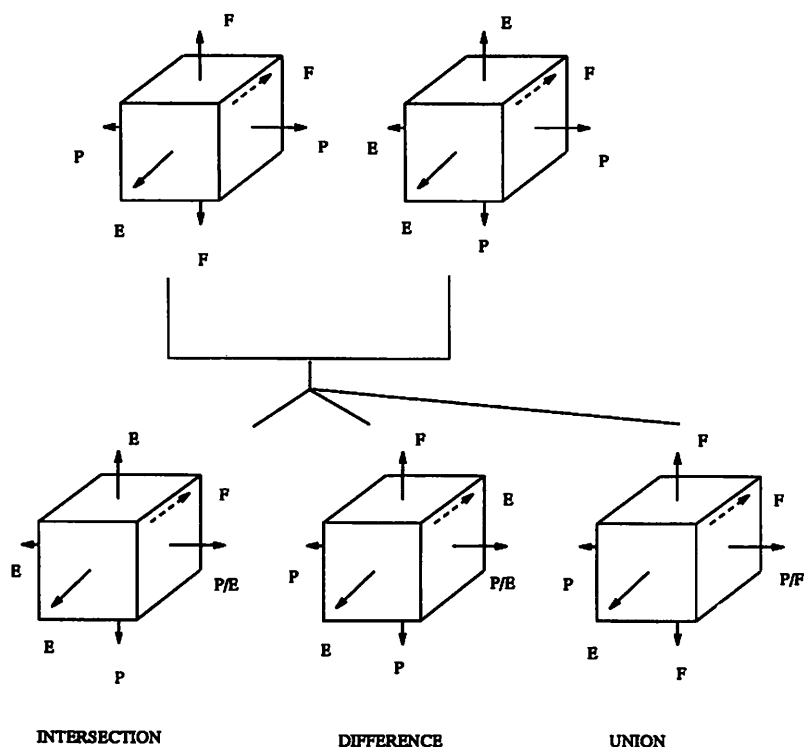


Figure 2 : Boolean operations on octree nodes.

advancement was estimated as 1.5cm.

The patient was scanned on a GE9800 with 35 slices. The voxel size was 0.86 by 0.86 by 5mm. It was necessary to remove the headrest from the scans by 2D ROI editing. Some artefacts were also removed.

The simulation stages were as follows :

A - Display(Patient) in Anterior, Left, and Right views.

B - Mark region R_1 in the Anterior view and Create_Mask $V1 = VOI_1$

C - Display_Boolean(Patient $\cap$ VOI_1) in Left view.

D - Draw region R_2 on this view, and Edit_Mask($V1$).

E - Specify the vector of translation by marking the anterior of the maxilla at one end, and the final position so as to cause closure of the open bite (T_2).

F - Form a new object (Translated_Maxilla) = Translate_Boolean(Patient $\cap$ $V1$)

G - Form the final object Prediction = Boolean(Translated_Maxilla $\cup$ (Patient - $V1$))

Figure 3 shows stages A to C of the above. The Anterior, Left and Right views are displayed with ROI_1 drawn on the Anterior view. The expression (Patient $\cap$ VOI_1) is shown in the bottom right, with ROI_2 drawn on this view. The translation vector was drawn by marking arbitrary points in space to close the open bite. The movement specified was reported as : (Forward 2mm Downward 1mm). Figure 4 shows the resultant of stage G in Left and Anterior views, contrasted with the same views of the original patient.

5 Conclusions

The need for a sophisticated surgical planning package includes the ability to dissect, transform and merge pieces of object. In the UCL3D system this is achieved using hierarchical volume descriptions of objects and masks, and standard octree algorithms for the manipulation. This volumetric approach combines the advantage of complete access to the data, with a space planning ability similar to CAD/CAM applications.

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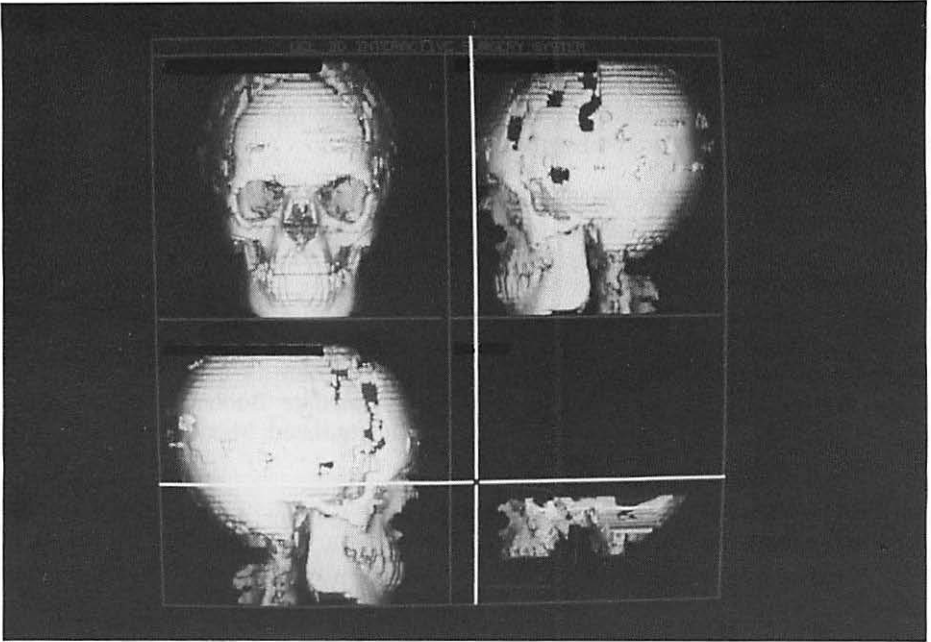


Figure 3 : Stages in simulating surgery on Patient 1.

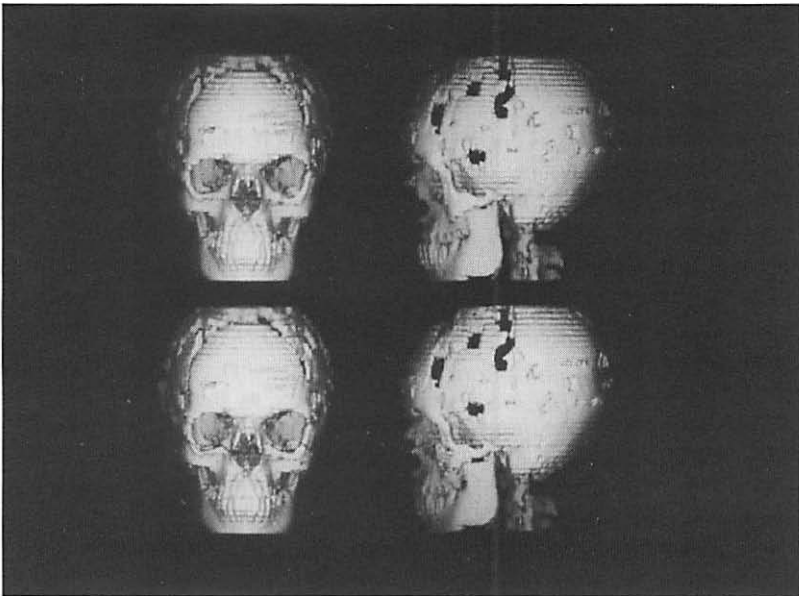


Figure 4 : The original and predicted hard tissues.

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Validation and Preliminary Clinical Trial of a Radiology Expert Computer System

Charles E. Kahn, Jr., MD

Department of Radiology, University of Chicago, Chicago, IL

2 yr. study.

in use ~ 2.5 yrs.

Non-radiologists.

Abstract The PHOENIX Radiology Consultant is a rule-based expert computer system which assists physicians in planning radiologic work-up strategies. This article describes the process by which the system's knowledge base was created and validated. Also, to test the feasibility and acceptability of the system, PHOENIX was placed in clinical trial for more than one year. During a period of 58 weeks, the system was used 473 times, an average of 8.2 times per week, primarily by medical students and nonradiology physicians. Much of the system's use occurred at night and on weekends, when the radiology department was not fully staffed. These findings suggest that an expert system can serve as a useful and informative component of a radiology information system.

Several investigators have applied artificial-intelligence techniques to problems in radiology such as procedure selection and differential diagnosis [1-3]. As with many other applications of artificial intelligence in medicine, these expert systems are developmental. To this author's knowledge, these systems have not been placed into clinical use and have not been evaluated thoroughly and systematically. This article discusses the validation and the preliminary evaluation of a radiology expert system.

The PHOENIX Radiology Consultant [4] provides information about the proper selection of radiologic imaging procedures. The system primarily was designed to aid nonradiologists, in particular, the housestaff physicians and medical students at our university teaching hospital. For a specified clinical problem, PHOENIX offers a recommended work-up strategy in the form of an algorithm or "decision tree"; physicians can view the algorithms and "move" through the decision tree to obtain more detailed information about the relevant rules and

*structured @
54 clinical problems
200 if/then
(production) rules.*

≈ 100 terminals in dept.

*26% weekdays
34% 8pm → 8am.*

213

imaging procedures. PHOENIX has knowledge of 54 common clinical problems, such as head trauma and pulmonary embolism, and of more than 75 radiologic procedures.

The algorithms encoded into PHOENIX's knowledge base were derived from our radiology department's imaging protocols as well as from several widely accepted references [5-7]. The algorithms were modified where necessary to ensure compliance with departmental standards. Three radiologists encoded the algorithms into production ("if-then") rules and verified the accuracy of the knowledge base by comparing the computer-generated algorithms with the source documents. Before full release, PHOENIX was made available only to our radiology department's section chiefs, who reviewed the computer-generated algorithms. This step provided a "peer-review" process to assure the accuracy of the computer system's knowledge. If the imaging work-up suggested by the computer system differed significantly from their own work-up strategies, these physicians alerted the system's developers. After several minor technical changes were made to the algorithms, the imaging strategies were considered valid and suitable for general release.

The system was made available to members of the radiology department in October 1987. This limited release enabled all attending and resident radiologists to evaluate the system and to detect any discrepancies between imaging strategies recommended by the computer system and those actually recommended by the department's physicians. PHOENIX was released for general use in December 1987. The system is available to members of our radiology department - staff radiologists, residents, technologists, and appointment clerks - at terminals distributed throughout the radiology department. Nonradiology physicians and medical students can gain access to the system from one terminal in the main radiology viewing room.

From June 15, 1988 until July 26, 1989, a period of 58 weeks, all encounters with the system were recorded. For each clinical problem selected by a user, the computer recorded the date and time, the user's ID code, and the location of the user's terminal. Medical students and nonradiologist physicians could gain access to the system at one terminal without a radiology computer ID code. During the period studied, the system was used 473 times, an average of 8.2 times per week. By far, the largest group of users were nonradiologist physicians and medical students, who accounted for almost three-quarters of total system use. Four staff radiologists used PHOENIX during the study

*≈ 10 uses / wk.
1046 uses over 730 days
mostly used by radiologist. path. VDTs in other cases =
increased use.*

period (16 encounters; mean 4.0 per person; range 2 - 9). Six of the department's 20 radiology residents used the system a total of 39 times (mean 6.5 per person; range 1 - 21). Seventeen radiology technologists and appointment clerks used the system 69 times (mean 4.1 per person; range 1 - 13).

Use of the system over weekends (Saturdays and Sundays, holidays not included) accounted for 30% of all encounters. Almost one-half of the use occurred between 6 p.m. and 8 a.m., when the radiology department was not fully staffed and attending radiologists were not present in the hospital. Of 54 clinical problems, the ten most frequently selected accounted for almost one-half of all encounters. Disorders of the chest were most commonly selected: widening of the cardiomedial silhouette, solitary pulmonary nodule and pulmonary embolism were the clinical problems most often viewed. All of the clinical problems were explored at least twice.

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Picture Archiving and Communications Systems

General Session

Functional Diagnostic Specifications for an Intelligent Radiology Workstation

Kenneth Levin

Division of Nuclear Medicine, Georgetown University Hospital,
Washington, DC

Abstract

This paper discusses the tasks that an Intelligent Diagnostic Radiology Workstation (IDRW) should be able to perform in addition to serving as an image review station. This discussion is focused on software. Hardware considerations are beyond the scope of this discussion. Included in our discussion are the types of data that an IDRW must handle. It is hoped that this discussion will lead to improved, friendlier, and more intelligent workstations which will be accepted by radiologists.

This paper discusses specifications for an intelligent diagnostic radiology workstation. The term "intelligent" is used to imply that more than just image management, transmission, and storage will be performed at this workstation. Artificial Intelligence (AI) software programs will be utilized in this system. It will be integrated into the hospital and radiology information systems so that the system can help monitor, control, and advise radiographers about the performance of individual examinations and will assist radiologists in the interpretation of examinations. The IDRW will also serve as a platform for obtaining the radiology report. There have been several recent papers concerning designs for Medical Image Workstations (1-5). The focus of this paper is integration of Hospital Information Systems, Radiology

Information Systems, and the IDRW and the role of AI software in making the IDRW a labor saving device which can assist radiologists in their tasks. This paper does not discuss hardware and display requirements.

One of the major problems limiting the integration of various computer systems is the lack of standardization. This hampers the development of IDRWs since these systems will have to interface with a hospital information system (HIS) and radiographic information system (RIS).

This paper is divided into three major portions. The first discusses input and output of an IDRW. The second discusses the functions that an IDRW should be able to perform. The third section discusses potential benefits of a IDRW.

1. Input and Output of an IDRW

An IDRW must deal with three different types of data. These are:

- a) Patient data, (input)
- b) Image data, and (input)
- c) Radiology report data. (output)

1a. Patient Data

This category of data is the data which is known before the radiographic examination is performed, i.e., patient history, physical examination, provisional diagnosis, results of previous radiographic examinations, results of non-radiological tests, and the reason the study was requested.

If these data were stored in a machine-readable format in a hospital information system (HIS), then an IDRW could search the database of the HIS to identify relevant input patient data and present this to the radiologist. However, many HIS systems do not have

data stored in a machine-readable fashion. This limits the possibilities for automation of data gathering by an IDRW. In those HIS systems that have machine readable databases, the lack of standards makes it difficult to develop an IDRW that can interface with different HIS systems, which is a necessity for economic viability.

The value of having patient specific data from the HIS available has been discussed in several papers. A paper from Grady Memorial Hospital discussed the THERESA/RadARS Systems (6). This system maintains individual patient records on-line and allows interactive analysis of the records with an English-like query language. The group from the Latter-Day Saints Hospital described a system for providing a radiologist with clinical data such as history, physical exam, and laboratory results (7). This system is a subcomponent of the HELP HIS system which was developed at the same institution.

1b. Image Data

Image data includes the current image and previous images. Recent developments in picture archiving and communication systems (PACS) show that technology for transmitting radiographic images is becoming useful and reliable. Decreasing cost/time/performance ratios and improving the user interface may lead to the acceptance of these systems in the not too distant future.

1c. Radiology Report

The radiology report is the output of the radiologist and IDRW, when film review is complete. This consists of the radiographic features present or

absent on the study as well as their locations, the interpretation of their implications, and a diagnosis. This could be represented in a computer database as the presence, absence, and location of radiographic features and a diagnosis. Annotation of the digital radiograph may be an innovative approach to the radiology report. The machine-readable internal representation can be available in English for humans to examine.

A variety of approaches to coding radiographic reports using computers have been tried. These have been reviewed in (8). These all utilize a common approach. First, specific radiographic features for each examination are determined. The radiologist then uses an appropriate navigation tool and marking device (either a computerized or a mark sense form) to indicate which findings are actually present. Some degree of quantification and confidence values are sometimes available. Recently, several computerized voice-to-text systems have been introduced to Radiology (9). These vary in their features: Some can interpret continuous speech, and some need interrupted speech. Some function using code words and features. Both the voice-to-text and the other systems have the radiographic feature as the common denominator of reporting syntax.

Recently, Haug, et.al., described an interesting computer program that uses as input free text radiologic reports and gives as output a list of radiographic findings, their location, and a diagnosis. This paper illustrates the bi-directional, one-to-one

correspondence between a database of radiographic features and a free text English language version of the report (8).

2. Functionality Model

The functionality of an IDRW could be modeled on the patient care duties of a radiology resident. This model is based upon practice in an academic radiology department. In private practice, other allied health practioners may perform some of these tasks. The ability of a computer to perform these tasks is discussed. This has been divided into three major sections: a) before an attending physician arrives, b) while an attending physicians is discussing the case (with the resident), and c) after an attending radiologist leaves.

2a. Before the attending arrives:

2a1. The radiology resident should be able to interact with the referring physician from the time a test is first being considered until after the report is complete. The resident should be able to discuss a patient's case and recommend an appropriate work-up. It has been demonstrated that computerized technology has this capacity (10-12).

2a2. The history for each case should be obtained, and if necessary, a physical examination should be performed. While it is not anticipated that computers will be able to perform a physical exam, if the patient chart is available in a machine readable form, the history and physical exam data can be searched. A history can be taken from a patient by a computer.

- 2a3. The type and format of certain studies must be specified. This could be performed by an advice system based on the information gathered above (13).
- 2a4. The radiology resident may do a study such as a barium enema. This would not be feasible with anticipated technology.
- 2a5. The current films should be loaded on the alternator. This is done by PACS systems.
- 2a6. Appropriate comparison films should be pre-fetched and loaded. This is not done by PACS systems currently; however, solutions have been proposed elsewhere (14). Radiologists may have different preferences for the layout of the images of the current and comparison studies on the IDRW. For example, on a 4 screen display one may prefer the current PA and Lateral chest x-ray on the middle two displays, with the respective comparison images on the outside displays, but another may prefer the current study on the right and the previous study on the left. The format for display could be individually designated in a 'personal preferences file' in the IDRW.
- 2a7. Each case should be examined as soon as performed to determine if the study is complete and to form a preliminary diagnostic impression of the study. This is not possible with computerized systems.
- 2a8. The resident should have knowledge of pathology, radiographic features, and image artifacts. Artificial Intelligence technology may allow an IDRW to "know" about pathology. This

knowledge is essential because it must be determined if the examination has adequately demonstrated the pathology that may be present before it can be considered complete. Some computer programs are capable of identifying specific radiographic features (15-17).

- 2a9. The size of lesions should be measured and recorded. This could be performed with machine assistance (18).
- 2a10. The attending physician should be informed of problem cases to allow timely intervention. This could be done by a machine based on information gathered in 2a1 and 2a2.
- 2a11. The attending physician should be informed when enough cases have been completed and it is time to review cases. An IDRW can indicate when enough cases have been assembled to allow review.
- 2b. When the attending arrives:
When the attending physician arrives to review, the history, the radiographic findings, the implication of these findings, and possible diagnoses for each case, should be discussed. If an IDRW has performed some of the data collection and image analysis functions discussed in 2a, then this can be presented to the radiologist. The discussion with the attending physician should be adequately documented. This is done by writing a brief statement in a log book.
- 2c. After case review:
 - 2c1. After the case review session, the cases should be dictated based on the notes

taken during film review. This can be performed interactively with an IDRW if the appropriate software and interface are developed.

- 2c2. Films should be removed and directed to storage, and any other paperwork involved should be cleaned up.
- 2c3. Referring physicians should be contacted about significant radiographic findings. If a phone number or beeper code could be autodialed by the workstation, it would ease this task. Machine to machine direct transmission of this information is also possible. An interface has recently been announced for the Kurzweil AI's VoiceMED system which allows the faxing of reports to physicians offices upon completion (19).

3. Discussion

In this section, I will discuss the benefits of having an intelligent diagnostic workstation which integrates patient data, image data, and report data. This will be divided into discussions of quality control and research; however, there is overlap of these two categories.

- 3a. There are several quality control features that can be implemented on an IDRW as discussed above. These consist of consistency checking, advice systems, order entry advice, and automated follow-up.

Consistency checking can be implemented on an IDRW. If a descriptor has changed between registration and report generation, i.e., the left knee is now called the right knee, the computer could test for this condition and point it out.

Embedded advice systems can examine the database of radiographic features the radiologist has observed for a case and offer independent advice as to a possible final diagnosis. This can be done with either advice systems or critiquing systems (20). This may prompt the radiologist to reconsider the diagnosis.

Computerized order entry with critiquing of choices can advise referring physicians of appropriate work-ups. This can act as a screen for inappropriate studies.

Automated follow-up of cases may be possible to allow the patient's final discharge diagnosis to be correlated with the radiographic reports that were generated during the patient's admission.

- 3.b The research benefit of an IDRW stems from integration of the Radiology report and patient specific information for research on patient outcome. For instance, for those patients who have ventilation/perfusion lung scans one would like to know if and when they have angiograms. One should be able to ask the IDRW to inform when this occurs. In addition, it should be easy to obtain cohorts of patients who have had a particular type of study or diagnosis for research and quality assurance purposes.

4. Conclusion

Incorporating some of these tasks into an IDRW should increase throughput, accuracy, income per unit time. This will lead to the acceptance of IDRW into radiology departments as labor saving devices.

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A Measurement Tool for Characterizing PACS Workload

L.E. Day, R.A. Hill, R.G. Jost and G.J. Blaine

Mallinckrodt Institute of Radiology, St. Louis, MO

ABSTRACT

In order to fully understand the network and archive requirements needed for PACS of the future, we believe it is important to move beyond models which are based on average daily activity. The introduction of actual digital system elements provides an opportunity to acquire, analyze and track the resulting workloads. Estimates of current image movement and storage requirements can provide a basis for sizing communications bandwidth and archive design. Alongside the need for data to support PACS design exists an administrative need for a flexible window to augment our Radiology Information System (RIS) in tracking departmental activity.

We have developed a prototype Workload Characterization System (WCS) to meet these two needs. The design of the WCS can be broken into three components: acquisition, storage, and retrieval. The acquisition component of the design centers around the concept of information "probes" that collect data on differing activities around the department, such as patient and exam information, digital image generation and movement, and network traffic. The storage component consists of a relational database (VAX Rdb/VMS) which integrates data from information probes. The retrieval mechanism provides an overall view of the data and the relationships among the data over an extended period of time.

1. INTRODUCTION

A Picture Archiving and Communications System (PACS) can be described by a deceptively simple model: 1) image sources, 2) image archive, 3) inquiry and display stations interconnected by 4) a

communications network. Many of the current PACS design efforts have utilized estimates of image traffic and storage requirements derived from observations of film-based operations. A phased introduction of PACS components offers an opportunity to gather and analyze workload data associated with generation, storage and utilization of images. Dynamic tracking of these activities is needed to support performance evaluation, design assessment and PACS system management.

In addition to PACS development and deployment needs, a timely view of departmental activity has proven essential to those making administrative decisions. A locally developed Radiology Information System¹ (RIS) currently fulfills many of our existing administrative needs. Data retrieval and presentation is based on pre-defined queries, and new views of the collected information require software development. A more flexible access, easily tailored by the user could enhance administrative utilization of the existing information.

A Workload Characterization System (WCS) has been designed to meet these needs. Information "probes" collect data describing department activity, and the information is forwarded and stored in a database as shown in the block diagram, Figure 1. The viewing mechanism provides an overall view of the data and the relationships among the data over an extended period of time. The storage component utilizes the relational database (VAX Rdb/VMS) to support viewing the data from many different vantage points.

2. PROBE DESIGN

In order to achieve efficient data acquisition, the Workload Characterization System utilizes independent probes that provide data to the database. A probe can be thought of as a process that reads samples of data from a source and produces samples for insertion into the storage system. Probe data collection methods vary with the data to be gathered. The probe can provide rate adaptation by buffering samples for block transfer to the database or data reduction by filtering or averaging data.

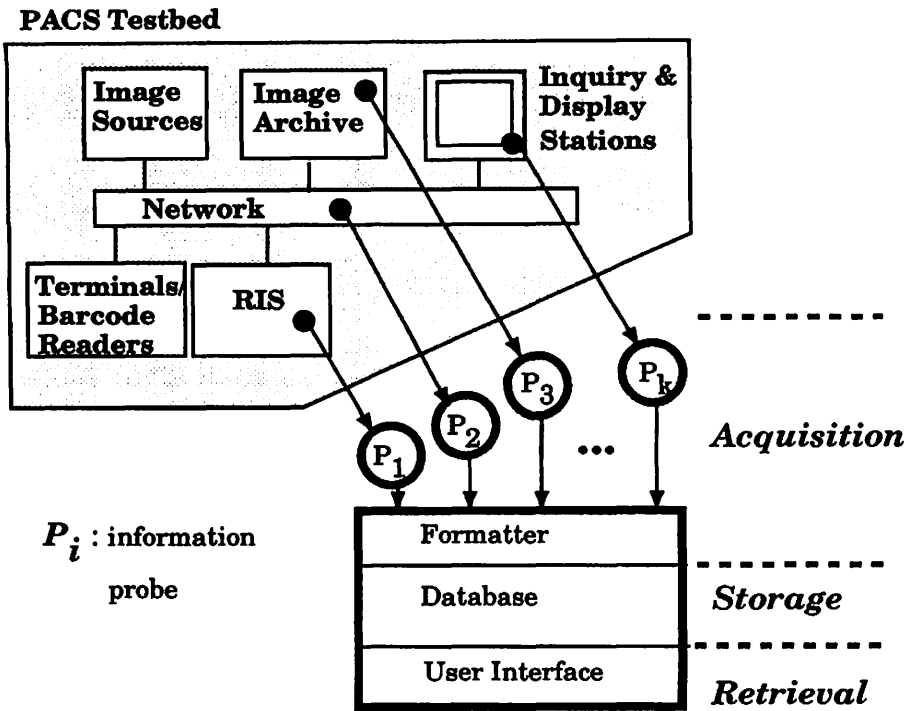


Figure 1. Block diagram of Workload Characterization System "probing" the PACS Testbed.

2.1 RIS Probes

Our RIS contains information about film movement, patient information, and exam information, but the custom nature of the database inhibits the use of queries by anyone except the designers of the database. Patient and exam information is stored in a Short Term File (STF) for 60 days, after which the information is transferred to a Long Term File (LTF) where it is kept for 5 years. In addition, all transactions that update the database are kept in a running log file which is compared to the day's actual database updates to insure the integrity of the database. Two RIS probes provide data to the WCS; one monitors the STF and the other monitors the transaction log.

The STF probe scans the RIS STF once per day, collects new entries and then updates the database once per day. The second

probe is the RIS Transaction probe, which monitors all of the transactions between the data terminals and the RIS database. Some typical transactions of interest are the adding of a patient or an exam to the RIS database or the movement of patients or film jackets from place to place within the department. Currently, a prototype Transaction probe is designed to sample the transaction log file once per day, with an output sampling rate of once per day. A second generation probe will be able to sample the transactions as they occur, producing an output sample for each transaction.

2.2 Image Probe

Another source of information is contained in the digital images, themselves. Currently, for example, Magnetic Resonance images from one of our MR scanners are being transferred to a short term image file on the DEC 8530 cluster located within our PACS testbed. The MR probe executes daily to obtain information from these images such as exam requisition number, number of images per exam and number of studies per exam and updates the MR relation in the WCS database.

2.3 Network Probe

A third activity of interest is the network traffic generated by image sources, archives, and viewstations. An Ethernet probe provides a statistical view of the Ethernet traffic between a group of PACS machines. A probe is dispatched for each image source and each image sink to be studied. An example of an image source is an MR scanner, while an example of an image sink is a viewstation. Typically, an archive requires two probes, one for the incoming images and one for the outgoing images. Each probe samples data from a locally developed Ethernet monitoring program, "WATCH", every hour over a 24 hour period and packages the data for later retrieval by a polling program that resides on the WCS database machine.

3. DATABASE DESIGN

The implementation of the database is based on a relational database (VAX Rdb/VMS). In a relational database, data resides in tables known as relations. In our initial implementation, a patient relation, an exam relation, and an image relation are linked via patient ID and exam identification numbers. System resource activity, such as

CPU, disk and network utilization are linked to the patient relations via time stamps. Example relations are shown in Figure 2.

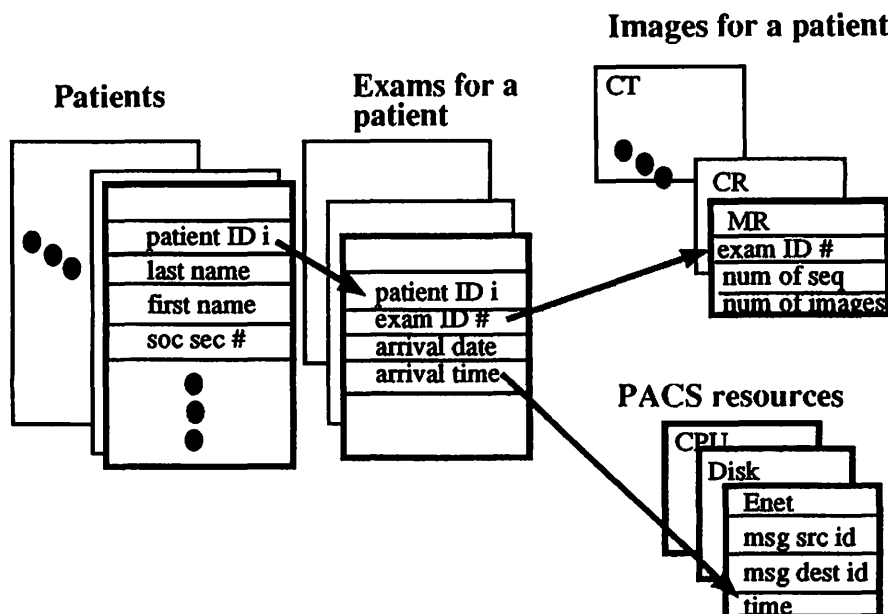


Figure 2. Example Relations in WCS

The *patient* relation contains general information about each patient using fields such as name, social security number, number of visits, MIR number, etc. extracted from the primary records of the RIS Short Term File (and the RIS Long Term File). The *exam* relation contains information regarding actions that have taken place during each specific patient examination. Fields in the *exam* relation include type of exam, exam ID number, patient ID number, patient arrival and departure times as well as other times such as report typed, report signed, films done, etc. The *image* relation contains a subset of the information found in the header of the image files. Fields in this relation include examination ID number, number of images per exam and number of studies per exam. The *PACS resource* relation contains information pertaining to the packet flow on the LAN, the percent of CPU utilization and disk channel utilization.

We can make use of data from multiple relations by creating logical views, consisting of a subset of records and fields from one or more relations in the database. To the user, a view looks exactly like a

relation, even though the records in the view are not stored together physically. We can combine information from the STF containing patient arrival and departure times with timing information extracted directly from the image sets to produce a more detailed look at the key events which occur during an examination.

4. RETRIEVAL

Data is retrieved for viewing using 20/20 (Access Technology, Inc.), a spreadsheet interface which accesses the RDB database through menu-driven queries. Menus prompt the user to specify criteria for the data search, data grouping, etc. The results of these queries are put into a spreadsheet which the user can manipulate using spreadsheet techniques and/or display in graph form. This interface is also adaptable for experts to write their own queries using the Data-trieve query language. Thus 20/20 makes data available to both expert and novice alike, creating a flexible and useful data retrieval mechanism.

Examples to illustrate a progressively finer viewing grain are provided as a collage in Figure 3. The total number of exams per day and the number of MR exams per day are plotted for a period of one month. The quantity of images per MR study and the Ethernet traffic in bytes per hour corresponding to transmissions from one of the MR instruments to the image archive are shown for a twenty four hour period.

5. CONCLUSIONS

Preliminary experience with the Workload Characterization System illustrates the utility of the design. A collection of specialized probes coupled to a high-level user interface promises a sustainable approach to system monitoring and analysis.

6. ACKNOWLEDGEMENTS

We thank Jim Studt for his contributions toward installation and utilization of RdB and 20/20 and his guidance on system software issues. Thanks to both Rex L. Hill and Allen P. Rueter for their participation in establishing access to the MIR RIS.

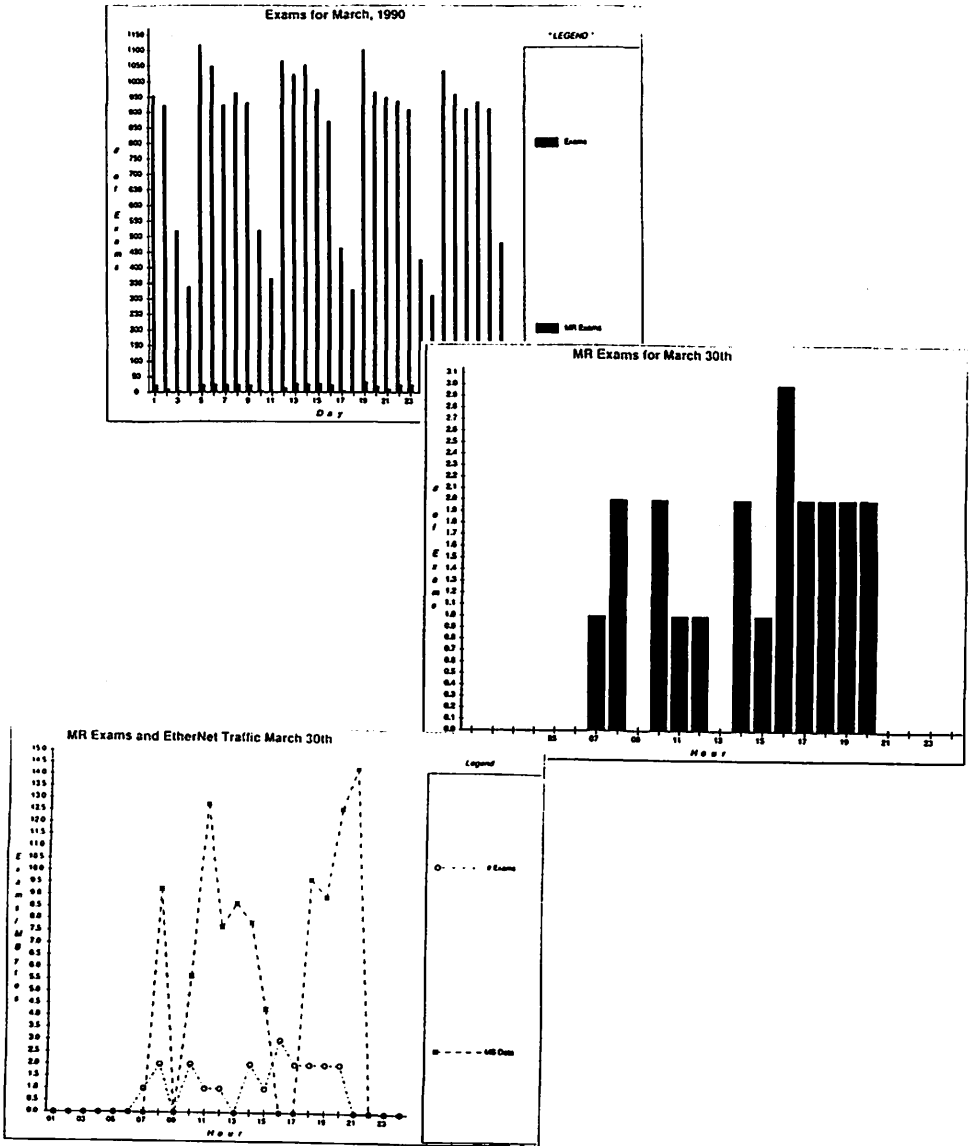


Figure 3. Collage of example results

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Overview of PACS Activity at MGH

R.A. Bauman, J.L. Taaffe, J.H. Thrall, et al

Department of Radiology, Massachusetts General Hospital,
Boston, MA

• INTRODUCTION

This paper will give a brief history of the work that has taken place at the Massachusetts General Hospital's Department of Radiology since 1984 in the area of PACS. Additionally, it will outline the development and direction that the department is now taking.

Founded in 1811, the Massachusetts General Hospital is a leading patient care, teaching, and research center. The 1084-bed facility, staffed with over 9,000 employees, is the original and largest hospital affiliated with the Harvard Medical School. The Radiology Department employs over 70 staff radiologists, as well as 50 plus film librarians to file and transport films. In addition, there are 51 research fellows as well as 34 medical residents. The RSTAR PACS development effort has grown over the past 5 years to the point that in January of this year it occupied an off site development facility in Cambridge in addition to space available at the main campus.

The 340,000 annual radiology exams would generate more than 5 Terabytes of digital data. Because of space limitations the department maintains a 15,000 square foot off-campus film library in Somerville in addition to the two on-campus libraries.

• PLANNING AND CONCEPTUALIZATION

Serious discussions and exploration of how to realize Picture Archiving and Communications System (PACS) began late in 1984. Initially, a significant obstacle to defining PACS functionality was the inability of radiologists and others to conceptualize and comment upon systems which did not exist and which had no adequate model from which to extrapolate. To overcome this problem with 'product definition' a traditional industrial style marketing study was initiated within the radiology department. In particular, a heavily illustrated, sixty page user's manual for a hypothetical system was written at MGH and completed February 1985. The manual was distributed to all members of the department and shortly thereafter comments were solicited and examined. This concrete exposition of a PACS facilitated visualization by radiologists not previously familiar with PACS. The manual's distribution and subsequent follow-up proved to be a powerful vehicle to obtain substantial feedback from the radiology staff and others.

• DEMONSTRATION UNIT

After incorporating the changes and insights garnered from the marketing study into our vision of a PACS, the next step in 1985 was the design and creation of a demonstration unit that in a very limited manner made real many of the features described in the revised users manual. The demonstration unit was capable of quickly displaying both CT, MRI, and nuclear medicine images upon multiple 512x512 pixel by 12 bit displays. The demonstration unit, based upon IBM PC type machines, included pull down menus, dialogue boxes, as well as graphic tools for operations such as window & center. The demonstration unit responded to mouse control as well as conventional keyboard command. Viewing and using this demonstration workstation facilitated and provoked further constructive dialogue with and among radiologists as well as the growing PACS development team.

• μ RSTAR

From these initial 'marketing studies' the demonstration unit and users manual goals were established. A development program was initiated to create a first generation PACS at MGH. One of the first major decisions the group faced was to either put all our efforts into creating a (then) high resolution 1K x 1k stand-alone workstation only or a complete network based system using less ambitious displays. We elected to build the system as opposed to just the workstation so that we could gain insight and experience in issues such as image transmission using local area networks (LANS), statistical image caching, large multiuser transactional databases, multi-modality on-line image collection, as well as managing off-line and removable image storage elements.

Knowing that this was to be at best a research system, hardware inexpensive enough to be discardable in the future was used. Software was to be done in a modular fashion to permit the forward transfer of major portions of the software to future versions of the system.

The project at the Massachusetts General Hospital (MGH) became known as RSTAR, Radiology Storage, Transfer, Analysis and Reporting System. The first generation RSTAR system is known as MicroRSTAR (μ RSTAR).

The initial μ RSTAR system used a VAX 11-750 computer (Digital Equipment Corporation; Maynard, MA) with 1.3 gigabytes (GB) of disk storage as the workstation server. The medical workstations are based on IBM AT class machines with a MGH modified display controller. Each workstation has a graphic control monitor and one to four 512x512x12 bit monitors with 4 bit color graphic overlays. A two-button mouse is used, and the cursor moves easily across all screens.

During the early development CT and MR images were entered into the system via magnetic tape. PET images were acquired directly though Decnet running over Ethernet. Nuclear Medicine images were acquired through an in-house designed and built acquisition node which includes a floppy disk drive capable of reading

Technicare VIP floppies and an Ethernet interface used to convey the data to the VAX.

Transmission of images to μ RSTAR workstations is done over standard Ethernet cable but uses an RSTAR engineered Ethernet protocol (registration numbers 8160 and 8161). This protocol, customized for transmission of large data sets (images) uses the techniques of multiple packet transmission per acknowledge cycle and auto-routing of packet data, operates without interference with standard DECnet, LAT, and TCP/IP protocols on the hospital's extensive Ethernet plant. Image transmission rates proved to be 10 times greater than that of DECnet PCDos.

μ RSTAR: Software and Functionality:

Whenever possible the RSTAR development staff purchased software, for example the graphic interface is based upon Digital Research Inc. GEM package. Nevertheless, the μ RSTAR software system included over 350,000 lines of code written by the MGH development group.

A few of the operational features of the system include password access, individual user configuration and preference files, algorithms for the automatic presentation of unread cases sequentially to radiologists according to their work assignments (for example, CT or MR, or all cases or only undictated cases), algorithms for the automatic initial placement of study images on available display screens with consideration of the study type, available screens, and user preference.

The initial window & center setting is accomplished automatically by an RSTAR histogram-based algorithm that sets four standard default buttons (for example, for CT they are Overall, Bone, Soft1, and Soft2). Additionally, window & Center may be adjusted by the user via either graphic sliders located on the control screen or via mouse movements --- vertical for window and horizontal for center.

The workstations support a wide variety of screen display options from one image per screen up to 64 per screen. Screens may be arbitrarily tiled for image display in both number of images per screen --- 1 to 64, as well as format --- square tiles as well as rectangular tiles may be used freely upon the same screen. The workstation supports multi-modality viewing upon the same screen. Cine loops can be constructed and mixed with static images. Additionally, cine speed loop speed and pause are controllable. The display programs correctly handle different image sizes and shapes. One, several or all of displayed images can easily be manipulated under mouse control, including zoom and roam, flip horizontally or vertically, rotate 90 degrees either direction, change from gray scale to pseudocolor display, clear graphics/annotations, and restore image to original state.

A wide array of measurement tools are available to the user such as length, area, arbitrary region of interest, and angle. All measurement results can be placed into VAX resident databases (Ingress from Relational Technology) or the VAX resident statistical analysis package (SAS from the SAS Institute). Also offered at the workstations but performed by the central VAX computer, are a wide array of

image processing tools, e.g., FFT tools, pixel normalization routines, image remapping routines, and image warping to name a few.

To aid the users of the system on-line help text is available by general topic, via table of contents and for any menu item or icon. Electronic mail is implemented (useful for feedback). To allow the μ RSTAR system managers to further be of assistance, the workstations can be enabled to send electronic mail to the managers upon various user activity (for example, login).

There are presently six μ RSTAR workstations in the department. Each of these workstations can retrieve and operate upon any image in the central VAX archive. Display time for a 512x512x12 bit CT image retrieved from the central archive is 2.8 seconds from time of request. All of the workstations have been used for the general display and the image processing and manipulation of CT, MRI and Nuclear Medicine studies. μ RSTAR was used to display vascular structures on MRI images very early as temporal cine data sets, prior to the widespread availability of commercial products. A particularly valuable, automated approach to Quantitative Bone Density determinations is in daily clinical use; it includes automated region of interest generation and calculation of data and control images for checking by radiologists. Nuclear Medicine digital images of all varieties have been archived since August, 1988; the nuclear images are available for recall and display for comparison to current studies.

• Q-RSTAR

Q-RSTAR is the name of the second generation MGH PACS system currently under development. With Q-RSTAR the emphasis has shifted from research to achieving clinical utility while continuing to test and learn from experience. An important Q-RSTAR goal is high resolution and high speed performance at an affordable price. Selected initial clinical applications will test the utility of this newer technology. Additionally, the goal of learning from a complete system continues as with the μ RSTAR project.

The Q-RSTAR display will include 2Kx2.5K pixel monochrome high frame rate display(s) with vastly faster communications via a dual local area network. More technical information is provided in other papers. Q-RSTAR features multimodality (CT, MRI, Nuclear Medicine, high resolution digitized images, etc.) and multimedia capability (orchestrated image, graphic, and voice). The central archive will be significantly expanded, but again no attempt will be made initially to handle the entire departmental volume. Performance includes transfer of 2K squared by 10 bit images from the central archive to a Q-RSTAR workstation in less than one second, and transmission of 512x512 byte by 12 bit images in less than 0.05 seconds each.

MGH Radiology is distributed in various buildings on the main Boston campus where radiology currently runs 100 megabit/second fiber optic cable (62.50 - 125 micron multimode fiber). Additionally, there are five other associated remote facilities where we currently run both 45 megabit/sec DS3 and 1.5 megabit/second T1 circuits.

The table below shows the deployment plan under way for Q-RSTAR workstations in addition to the μ RSTAR workstations already in place.

<u>Location</u>	<u>Type</u>
MRI @ Charlestown	1 screen 2K x 2.5K
MRI @ Charlestown	1 screen 1.2K x 1K
Tower-Dodd Room	2 screen 2K x 2.5K
Robbins Room	1 screen 2K x 2.5K
ACC-5 (bone)	2 screen 2K x 2.5K
ACC-2 (chest)	2 screen 2K x 2.5K
White-1 Emergency Room	2 screen 2K x 2.5K
White-2 Display/Demo Room	1 screen 2K x 2.5K
Nuclear Medicine Interpretation	1 screen 1.2K x 1K
Nuclear Medicine Interpretation	1 screen 1.2K x 1K
White-2 Display/Demo Room	2 screen 1.2K x 1K
Spaulding Rehabilitation Hospital.	1 screen 2K x 2.5K
Suburban HMO.	1 screen 2K x 2.5K
Cambridge RSTAR development center	1 screen 2K x 2.5K
Cambridge RSTAR development center	1 screen 2K x 2.5K
Cambridge RSTAR development center	2 screen 1.2K x 1K

• PACS FIELD TRIALS

To best understand the PACS activity at the MGH it is best to present it in terms of field trials that we will begin late in 1990 and for which we are actively engaged in development.

On Demand File-Digitization from Our Main Film Library:

The MGH Emergency Room and the Ambulatory Care center at the main campus frequently request patient images stored in the remote film library located several miles away in Somerville. Currently, Somerville is called to request that the original images be sent to the main campus on the next shuttle bus which operates between the locations hourly during the day.

This field trial will test the concept of on-demand remote-image-digitization of requested images at the remote film library and immediate transmission over a broadband network via the department's Q-RSTAR system. Upon entry in Q-RSTAR, these images will be available for viewing on any Q-RSTAR workstation in the radiology department or as laser printer produced hard copy. A number of DuPont FD-2000 210 micron resolution scanners are used that will scan an image in 6 seconds.

Communications to the Charlestown MRI Out-Patient Facility:

The Charlestown facility conducts all outpatient MRI studies. Although MGH radiologists staff this facility, some MRI studies need to be read at MGH. Conversely, radiologists at Charlestown need to access studies conducted at the main campus, such as CT. Additionally, there is a need for radiologists at the main campus and at Charlestown to consult with each other on a study.

A DS3 and a T1 circuit connects Charlestown and the main campus. Two GE-Signa scanners are in process of being interfaced to Q-RSTAR using TCP/IP via Ethernet. Additionally, two Q-RSTAR workstation will be placed at the Charlestown facility. The aim of this trial is two-fold; first, to determine whether Q-RSTAR can be used as the primary archive for clinical MRI studies, and second, to determine if multimedia workstations can be used to effectively 'shrink' the distance between the two facilities. Additionally, physicians in the MRI facility should benefit from access to other patient images.

Support to the Spaulding Rehabilitation Hospital:

MGH provides complete radiological service to this affiliated hospital. Spaulding possesses only conventional x-ray equipment. Patients requiring CT scans are sent to MGH; patients requiring MRI scans are sent to the MGH outpatient facility in Charlestown. Both a high resolution workstation and a film digitizer will be placed at Spaulding to permit viewing and interchange of studies on Spaulding patients at any of the imaging facilities.

Support to a Suburban HMO:

There are many HMOs and imaging centers without proper access to radiological services, in particular, radiological sub-specialists. The goal is to investigate whether it is possible to yield high quality radiological service by placing a high resolution film digitizer at the HMO, digitizing the images, sending the image data to MGH via a DS3 circuit, and lastly, providing immediate consultation when appropriate and a written report later. If this field trial goes well, a high resolution workstation will be installed at the HMO.

Support to the Radiology Department:

The main focus of evaluating RSTAR resides in the MGH Radiology Department itself, in spite of the important external activities. The critical question is whether the introduction of PACS improves patient care. In this regard the PACS development group will be working closely with the MGH Radiologists and support staff in incorporating PACS technology into the workings of the Department.

It is believed that the Q-RSTAR system will be a solution to the emerging problems associated with the existing film based image management systems. In particular, the problems due to the increasing volume of image creation, the increasing demand for image access, and the requirement to increase retention of images. In essence, it is believed that Q-RSTAR will not only be a PACS but a work-flow management tool for the department.

Calling the above five items 'field trials' does not imply that they are only temporary 'experiments'. It is intended that the service will continue if the field trial is successful.

In summary, this is an exciting time for the Department, the hospital, the many participating institutions, and especially for the PACS development group that has worked over the past five years.

We would like to take the opportunity available to us and thank the many companies that have aided us over the years, particularly:

**Digital Equipment Corporation,
Honeywell Magnetic Memory Products,
and
Nynex Science and Technology**

Functional Design of a Folder Manager on an Image Archive

*Sridhar B. Seshadri, Sheel Kishore,
Satjeet Khalsa and Ronald L. Arenson*

Department of Radiology, Hospital of the University of Pennsylvania,
Philadelphia, PA

1. ABSTRACT

The Radiology Department at the Hospital of the University of Pennsylvania is currently expanding its prototype Picture Archiving and Communication System (PACS) into a fully functional clinical system. The first phase of this expansion involves three major efforts: the upgrade of the 10 Mbit token-ring to an 80-Mbit fiber-optic backbone, the implementation of a large-scale image archive, and, the implementation of a software suite called the Folder Manager. The Folder Manager has been designed to duplicate and enhance the operation of the conventional film library. This paper discusses the functional design of the Folder Manager and its role in image acquisition, archival and display.

2. INTRODUCTION

The Radiology Department has been operating a prototype Picture Archiving and Communication System (PACS) since 1986 [1]. Efforts are underway currently to convert the prototype PACS into a fully functional system over the next several years. The first phase of this expansion is designed to meet the archival and display requirements of five Magnetic Resonance (MRI) Scanners and three Intensive Care Units (ICUs). Details regarding the hardware implementation are described elsewhere [2]. In order to duplicate and enhance the operation of the conventional film library, a consistent software architecture has been developed. It consists of a suite of processes collectively known as the Folder Manager (FM). The Folder Manager consists of four functionally separate software modules: the Message Manager (MM), the RIS/PACS Translator (RPT), the Database Manager (DBM), and, the Patient Manager (PM). Each module has been designed to duplicate the operation of a specific aspect of the conventional film library. It is important to note that while the Master Folder Manager resides on the image archive node, a subset of the FM operates at every acquisition and display node. The design philosophy of the FM is described elsewhere [3].

Following the discussion in [4], we have developed specific dataflow scenarios that describe the interaction among the various components of the Folder Manager. The dataflows address the following functions:

- Examination Acquisition using scheduling information from the RIS
- Examination Acquisition without scheduling information from the RIS
- Examination cancellation from the RIS
- Examination Display: Automatic and On-Demand

We now discuss each of these scenarios in greater detail. The following notation is used in the figures:

FM	Folder Manager: a collective term for the MM, DBM, RPT and PM
•MM	Message Manager: the primary server in the PACS; an information router
•DBM	Database Manager
•RPT	RIS/PACS Translator
•PM	Patient Manager: responsible for the higher-level optimization of the PACS
RIS	Radiology Information System. In our case DECRad
IARS	The Vortech Image Archival and Retrieval System. The <i>Vortech IARS</i> is a large scale image archive capable of storing between 25GBytes and 7.68 TeraBytes on-line.
MIG	The Vortech Medical Imaging Gateway. The <i>Vortech MIG</i> is a computer system designed to provide standard connectivity between multiple-vendor acquisition/display devices and a standard PACS.

3. FUNCTIONALITY

3.1. Image Acquisition using scheduling information from the RIS

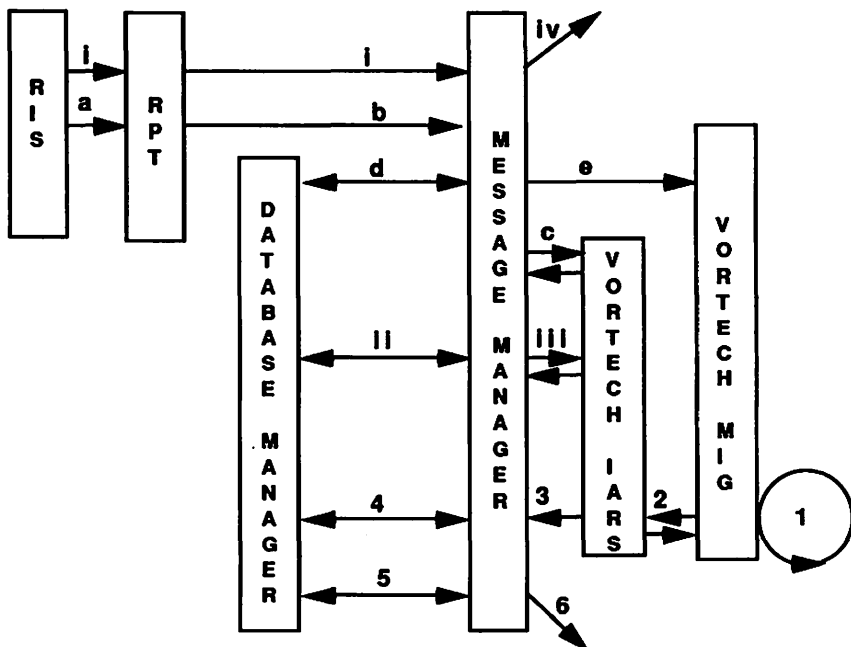
There are three major transactions in this scenario: EXAMINATION SCHEDULE (denoted by 'a' through 'e'), IMAGE PRESTAGING('i' through 'iv'), and, IMAGE ACQUISITION ('1' through '6'). We now discuss each of these in greater detail.

EXAMINATION SCHEDULE: The RIS initiates the transaction by sending an Exam Schedule notice to the MM via the RPT ('a', 'b'). The MM requests and receives image handles from the Image Archive ('c'). The scheduling information is sent to the Image Database ('d'). Finally, the demographic

information is sent to the MIG ('e'). This is done to decrease operator intervention when the images are actually acquired.

IMAGE PRESTAGING: In general, it is desirable to decrease the volume of burst traffic on the network. To achieve this goal the FM estimates the number of 'previous' comparison examinations that will need to be viewed and transmits them to the display node. Prestaging begins with a trigger going off based on an internal timer or patient arrival ('i'). The MM and the DBM communicate with each other to generate the list of previous examinations (ii). A request is sent to the IARS to pre-stage the images in the previous examination(s) (iii). A PREVIOUS_EXAM folder is constructed and sent to the display node (iv). Note that the actual pixel data is not transmitted at this time.

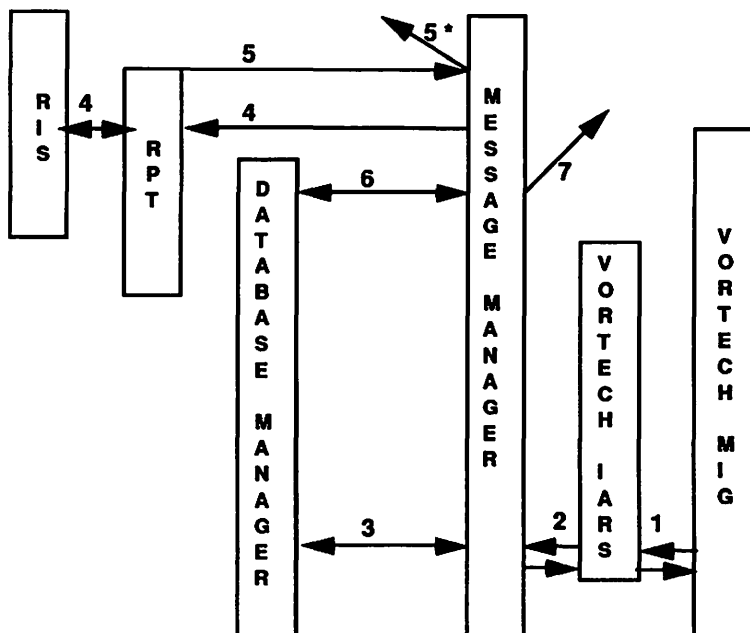
IMAGE ACQUISITION: To decrease data-entry errors it is advisable to keep operator data-entry to a minimum. With this in mind, the FM sends the demographics information to the MIG controlling the acquisition device (see *EXAMINATION SCHEDULE* above). At the time of acquisition, the technician would strobe the schedule notice associated with the examination using a bar-code scanner. The barcode scanner would be connected to the MIG servicing the acquisition device. Using the accession number read off the schedule notice, the MIG would search for the demographics that have been previously sent to the MIG ('1'). If the demographics are found, the operator would scan the appropriate image(s) which would be sent to the IARS ('2'). The IARS then strips the headers from the image and sends them to



the MM as ACR/NEMA messages ('3'). The MM collects the images comprising the exam in a folder and adds the exam to the database ('4'). The final step is to send the current examination in the form of a folder to the display node ('5', '6'). Note that a possible enhancement in order to expedite the receipt of exams at the display node is to simultaneously transmit image information both to the IARS as well as the display node.

3.2. Image Acquisition without using scheduling information from the RIS

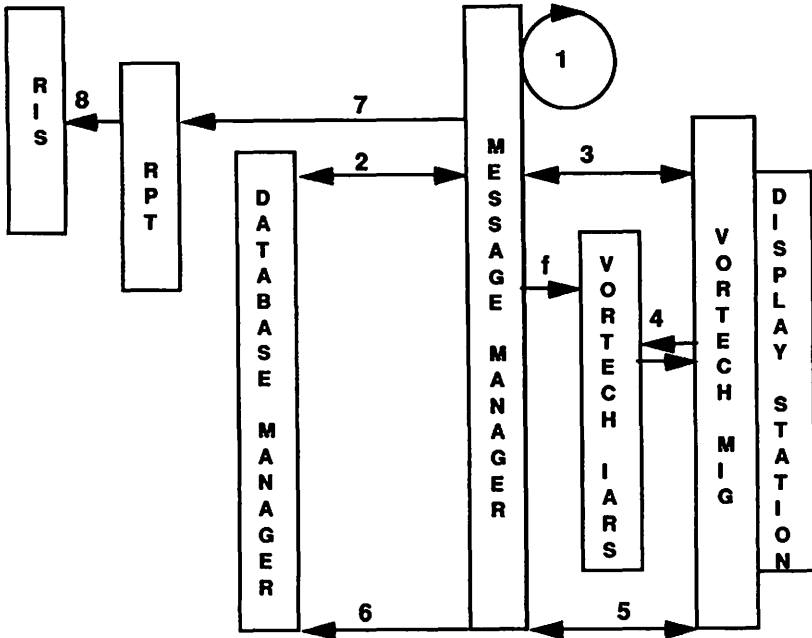
It is not possible to guarantee that the RIS (or the RIS/PACS link) will be operational at all times. We now discuss the method for adding examinations without an operational RIS/PACS link. The MIG does not have the demographics information sent to it prior to the examination (*see Section 3.1*). Therefore, the operator enters the demographics information and scans the images. The images are then sent from the acquisition node to the IARS ('1'). As before, the image headers are stripped and sent to the MM ('2'). The MM collects the incoming information in holding tables, and once the exam is complete, transmits the exam information to the DBM ('3'). Note that if the DBM has had prior knowledge of the examination/patient, the information is considered verified and is entered into the database. Otherwise, it is flagged as unverified. If the exam information is unverified, an attempt is made to match the information with the RIS ('4') and the results of the match are sent to the MM ('5'). If the match failed, the MM enques the exam for manual correction ('5*'). If the match succeeded, the database is notified. This triggers a current examination folder ('6') which is sent to the display node ('7').



3.3. Examination Cancellation from the RIS

For a variety of reasons the RIS could cancel a previously scheduled examination. To discuss this situation we assume that the events described in Section 3.1 have already occurred. Once the cancellation notice is received from the RIS, it is sent to the RPT ('1'). This notice is then forwarded to the DBM via the MM ('2', '3'). The DBM takes appropriate action to delete its entries.

3.4. Examination Display: Automatic Folder Generation



If it is possible to predict when and who will view radiological image information, it is desirable to be able to send the required images to the display node in advance of the viewing session. To enable this functionality, the MM has been designed to operate with a rule-base that is capable of generating triggers which will initiate a send to the workstation ('1'). When this trigger occurs, the MM communicates with the DBM to retrieve a folder from the database ('2'). The MM then sends the current folder to the MIG ('3'). At its convenience, the MIG retrieves the images from the IARS ('4'). Note that since the MIG is responsible for managing its local store, it is advisable for the MIG to get images rather than have the IARS send the images to the MIG. After the viewing session, the results (which may include the dictated report) are sent to the DBM via the MM ('5', '6'). Simultaneously, the MM also sends the results to the RIS via the

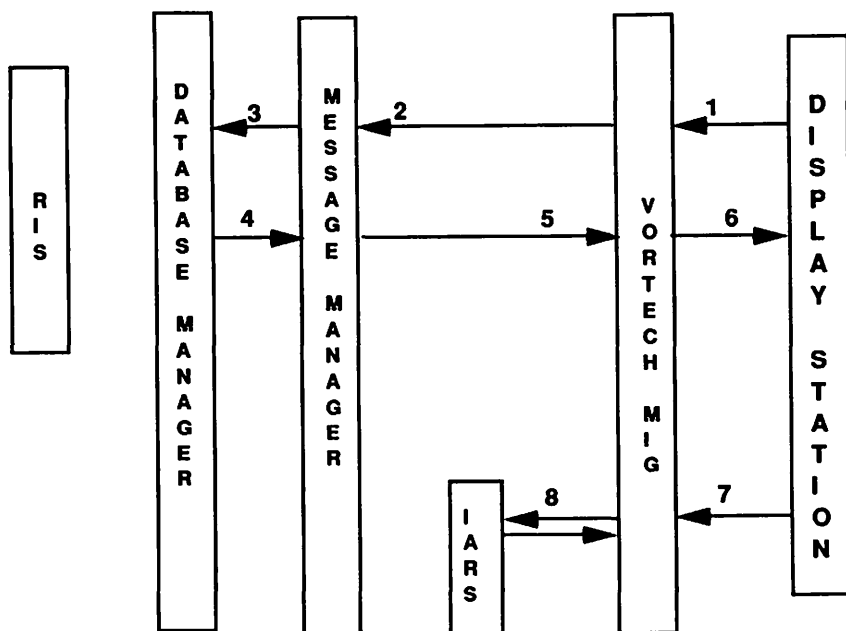
RPT ('7', '8').

3.5. Examination Display: On Demand

The Automatic Folder Generation described in Section 3.4 will not provide sufficient functionality for all possible situations. Consequently, the PACS should attempt to minimize the radiologist wait-time when an 'on-demand' request occurs. The FM does this by analyzing the radiologist's request, and making a decision based on the volume of pixel data to be transferred.

If the FM estimates that the radiologist's request will translate into a large volume of pixel data (and consequently a long delay) it queries the database and sends a list of exams (and relevant descriptive information) to the radiologist with a request to further refine his viewing list. Once this is done, a folder ('folder by reference') similar to the one described in Section 3.4 is sent to the MIG associated with the display. The display station then retrieves the image information. We now discuss a possible scenario in greater detail.

The radiologist requests an exam for viewing ('1'). The request is forwarded to the DBM via the MM ('2', '3'). The DBM responds with a list ('4') which is returned to the MIG via the MM ('5'). The MIG forwards the list to the display station with a request to the radiologist to further narrow down the selection ('6'). The radiologist makes the selection which is passed to the MIG ('7'). The MIG retrieves images for display ('8').



4. SUMMARY

A software suite called the Folder Manager has been designed and implemented on the Vortech IARS. The goal of the Folder Manager is to optimize the acquisition, communication and display of radiological images on a PACS. The software is currently under β -test.

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PACS Clinical Evaluation

Digital Chest Radiography in a Trauma Center

Helen T. Winer-Muram, Robert E. Gold, Scott Baum, et al

University of Tennessee, Memphis, Regional Medical Center
at Memphis, TN

Introduction

A Level 1 Trauma Center creates an intense medical environment targeted at a limited spectrum of high risk disease. In the trauma intensive care setting a digital imaging system must satisfy the requirements for radiography of the chest, since twenty-five percent of trauma-related deaths can be attributed to chest injuries. This study was undertaken to determine whether digital radiography is of sufficient diagnostic accuracy, in the Trauma Intensive Care Unit (TICU) setting, to replace our current analog system. The chest film examination was selected as the subject of the study because of its importance to the TICU patient.

Materials and Methods

Acquisition of the study population took place over a three month period from January, 1990 through March, 1990. All images for interpretation were acquired from the TICU patient population of the MED using portable radiography. The MED has a maximum capacity of eighteen TICU beds. Each day, three patients were filmed on both the analog and digital systems. No patient was restudied until the entire remaining population of the TICU was included in the study.

All digital examinations for this study were acquired using a Siemens Digiscan Computed Radiography system. The digital images were exposed on 14"x17" ST3 cassettes and were interpreted from film at a 2:1 reduction factor. A

second processed image of the digital study was also available for viewing on the same film.

The conventional and digital examinations were both exposed with radiographic parameters considered optimal for the conventional study. If the conventional examination was considered technically inadequate by the interpreting radiologist or the technologist, that set of radiographs was eliminated from the study.

The study attempted to simulate the normal circumstances of film interpretation for our TICU. No clinical histories were provided other than the knowledge that these were all TICU patients. No limitation in diagnoses was imposed on the readers. A complex form was designed to cover all diagnostic possibilities on chest examinations and the readers completed this form during or immediately after their interpretation of each radiograph.

A brief explanation of the contents of the form was provided each radiologist before their first reading session. An additional brief introduction to the concept of reporting images appropriately for ROC analysis was provided for each reader. A total of six board certified radiologists read each study. Three radiologists read the conventional examinations first and the other three read the digital examinations first.

At the completion of all readings, all six involved radiologists convened and reviewed the combined digital and conventional films as a panel of experts. Consensus of the panel on each feature of the examination constitutes truth for the purposes of this study.

Results were analysed using a chi-square analysis. Because of the small number of patients in some cells, Yate's correction was applied when the p value was calculated.

Results

Fifty-six conventional and fifty-six digital chest examinations obtained on thirty-seven patients were each interpreted by six board certified radiologists. In all cases, this was the first opportunity for the radiologists to interpret digital radiographs.

The film interpretations were divided into positive and negative findings. Inconclusive interpretations, "possibly present" and "possibly not present", were not included in either the positive or negative groups. The results are summarised in Table 1. There was no significant difference between the interpretation of the analog and digital films in all categories except for mediastinal hematoma. In this category, analog films were superior to digital ones. A more detailed statistical analysis will be presented.

Table 1

Abnormality	Conventional		Digital		p Value
	(+) ve	(-) ve	(+) ve	(-) ve	
Air space disease	173	103	190	84	n.s.
Interstitial	102	158	86	154	n.s.
Mixed pattern	49	191	55	177	n.s.
Mass	6	298	2	285	n.s.
Emphysema	7	299	9	285	n.s.
Mediastinal hematoma	21	244	9	255	<0.04
Effusion	89	141	83	142	n.s.
Pneumothorax	12	288	8	280	n.s.
Pneumomediastinum	9	306	8	316	n.s.
Spinal fracture	5	147	4	165	n.s.
Rib fracture	87	201	84	187	n.s.
Hilar adenopathy	1	264	1	253	n.s.
Mediastinal adenopathy	1	256	0	260	n.s.

Discussion and Conclusions

This study represents an attempt to evaluate the effectiveness of digital radiography in the "true-to-life" clinical setting in which a radiologist evaluates all possible findings on a radiograph, rather than focusing on selected findings thought to test the resolution of the system. All radiologists involved in this study were considered novices

in regard to digital radiography and the study design itself is felt to be extremely arduous by comparison to a study that evaluates only one or two features, such as pneumothorax.

The data presented is considered to be preliminary data from a much larger and ongoing study in progress.

This preliminary study demonstrates that for the most part, digital films are comparable to analog films. However, the presence of mediastinal hematoma was recognized less frequently on digital films. While this deficiency may have been caused by the limited experience of the investigators, it may reflect an area in which analog films are superior to digital films or may be caused by the reduced size of the digital image compromising estimation of mediastino-thoracic ratio. Later results from our ongoing study are expected to determine whether digital radiographs are accurate enough to replace analog radiographs in a TICU.

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Display of CT Studies on a Two-Screen Electronic Workstation Versus a Film Panel Alternator: Sensitivity and Efficiency Among Radiologists

W. Dennis Foley, Donald R. Jacobson, Andrew J. Taylor, et al

Department of Radiology, Medical College of Wisconsin, Milwaukee, WI; Department of Radiology, University of Nebraska Medical Center, Omaha, NE; and Section of Management Engineering, Milwaukee County Hospital, Milwaukee, WI

ABSTRACT:

Prototype electronic workstations incorporated in networks linking computed tomography and magnetic resonance imaging systems are being developed. A comparative evaluation of observer efficiency and sensitivity in reading body CT studies from a two-screen workstation (1000 line monitors and 12 bit dynamic range in image memory) and conventional film panel alternator was performed. The two-screen workstation displayed 32 images at 256^2 matrix resolution or 8 images at 512^2 matrix resolution simultaneously. Ninety-six images at 512^2 matrix resolution could be displayed simultaneously at the film panel alternator. Four observers read 20 case studies, 10 with repeat examinations, in a randomized viewing sequence. There was an average of 32 images per case. Reporting time on the film panel alternator was faster (Film Panel Alternator - average = 5.07 minutes, workstation - average time = 6.66 minutes). Extra analysis time at the workstation was required if observers analyzed cases initially at 256^2 resolution and subsequently at 512^2 resolution. There was improved sensitivity by all observers in reading from the Film Panel Alternator (range 1-12%)($p < 0.05$).

In reading complex body CT cases, the current prototype two-screen electronic workstation is limited by display capabilities.

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INTRODUCTION:

Multiscreen workstations linked via network to primary imaging systems and with on-line and off-line electronic storage are projected to be the diagnostic hub of a Radiology Picture Archiving and Communications System (PACS). While the resolution requirements for the electronic display and diagnosis of radiographic images, particularly chest radiographs, have been extensively studied¹⁻¹³, requirements for the accurate and efficient reporting of multiple lower resolution cross-sectional images from a multiscreen display station have not been addressed. While a total radiology PACS is not practical unless digital radiography can be implemented effectively from an economic and diagnostic viewpoint, mini-PACS linking CT and MRI systems to a multiscreen workstation are a near term possibility. A workstation can be used for on-line monitoring and review of current studies from multiple imaging systems. In addition, the workstation is a potential replacement of the film panel alternator for study reporting and, via connection to an electronic archive could lead to the replacement of film as the archival medium for CT and MRI studies.

In this study, we evaluated the capabilities of a prototype two-screen electronic workstation for reporting and based on these initial results suggest modifications and improvements to the current prototype system.

Materials and Methods:

Twenty body CT studies which were performed in 1987 and for which either a tissue or conclusive clinical diagnosis was available were chosen. Cases were selected from consecutive studies beginning at a fixed time point (June 1, 1987) until a representative series of studies related to trauma, inflammation, vascular disease, detection and staging of malignancy and diffuse organ disease were available. Selected cases demonstrated focal or multifocal pathology in the neck, thorax, abdomen and pelvis and contained an admixture of readily perceived and subtle abnormal findings varying in size from 5 mm diameter (focal lung lesion) to several centimeter masses (focal pancreatitis, hepatic metastases, pulmonary metastases, abdominal aortic aneurysm, et cetera) to diffuse organ disease (e.g. cirrhosis). The cases were typical of those seen in a tertiary care medical center performing 7000 body CT exams per annum. There were two cervical, two thoracic, two thoracic/abdominal, six

abdominal, seven abdominal/pelvic and one pelvic CT studies. The diagnostic findings, for each anatomic area are outlined in Table I. In ten of the patient studies, two CT examinations were performed. In each of these ten cases, both the images and diagnostic impression from the initial CT study were pertinent to interpretation of the second examination. The list of diagnostic findings, both pertinent to patient management and incidental for each study was established by an expert panel who reviewed all the CT images and the pertinent clinical information and tissue diagnoses, if available. The expert panel did not relate any of the selection criteria or specific diagnoses to the observers who participated in the experiment.

The cases were read by four experienced radiologists who had acquired familiarity with the operation of the electronic workstation by reviewing studies from a remote imaging system and/or transmitting selected images from the electronic workstation to a physicians viewing station elsewhere in the hospital. All four radiologists were experienced body CT readers, but had not previously diagnosed studies from the two-screen display station. The readers analyzed each case from the two-screen electronic workstation and from a film panel alternator. Each reader was provided with a pertinent clinical indication for CT study, equivalent to what would be expected during normal radiology reporting. To approximate the daily working environment as closely as possible, the descriptive report and impression were dictated onto an audio cassette and subsequently transcribed.

For the study format, each reader initially read ten cases from the film panel alternator and the other ten cases from the electronic workstation. For the film panel reading, each case was displayed on a 12/1 multiformat film with a standard window level settings appropriate for neck, thorax or abdominal studies. Thoracic studies were also filmed at "lung windows." Cases with skeletal pathology (e.g. vertebral metastases) had images displayed at bone windows. These studies were arranged on a 50 panel alternator which allowed two panels to be viewed simultaneously, each panel allowing four films or 48 images to be displayed. Thus, a reader had direct access to 96 512^2 matrix CT images without manual change of the film panels. Each neck, thorax or abdominal study could be read from one film panel. In the ten studies in which progress thoracic or abdominal CT examinations were

performed, both the preliminary and subsequent CT study could be evaluated on the two panels simultaneously. For the thoracic/abdominal CT studies, the thoracic or abdominal sections of the two studies could be compared simultaneously, but not both together. All patient identification marks on the film display were covered.

The electronic workstation utilized two video monitors, each 1280 horizontal lines operating in a 60 Hertz non-interlaced format with a bandwidth of 78.6 MHz providing a 1024 x 1024 image display (General Electric Medical Systems, Milwaukee, Wisconsin). The video monitors were 19" oblique diameter and displayed menu options and patient identification at the upper and lower margins of the screen. The image data was displayed using a dynamic range of eight bits with an interactive window width and window level function allowing evaluation of the full 12 bits of image data.

Screen luminance for a water density object (using a window level of 0 and window width of 350) was 55 cd/m^2 for the film panel display and 6.2 cd/m^2 for the video screen (Fig. 1). Screen luminance was linear over a wide range of tissue densities for both viewing modalities except for the more transmitting components of the image (e.g. contrast material and bone) (Fig. 1). The film display had a slightly greater contrast than the video screen. The screen illuminance (the light level incidence on the screen from surrounding room lights) was approximately 33 lumen/m^2 at the average ambient light levels employed in the experiment.

At the electronic workstation, 512² images were displayed 4/1 on each screen and 256² images were displayed 16/1 on each screen. The video screens could be operated in a "merge" mode allowing 32 consecutive images from one study to be displayed. Alternatively, with the "split screen" mode, different studies of the same patient could be displayed on each screen and compared. Instantaneous window level controls to preset values for soft tissue display of the neck, mediastinum and abdomen and for display of lung parenchyma and skeletal structures were provided. The window width and window level display values were equivalent to those utilized for film display of these regions. Additional window and level changes could be made by each reader using a "mouse" control. Thus, each reader could interactively change contrast

throughout the full dynamic range of the video display, while the range of contrast displayed on the film images was fixed.

Cases were selected from a displayed list using the interactive mouse and menu screen prompts. Screen display times for eight 512^2 images was 7.5 seconds and for 32 256^2 images was 26 seconds. Cases to be displayed at the electronic workstation were preloaded onto a 600 Megabyte magnetic disk incorporated in the workstation.

Four weeks after the initial two reading sessions (10 cases read from the film panel alternator in one session and 10 read from the electronic workstation in the other), the cases were reread from the alternate viewing modality using a different random sequence. Thus, each observer participated in four reading sessions. Reading time varied between 45 and 90 minutes dependent upon reader speed. No time constraints were put on the individual reader.

The dictated reports were analyzed for the readers' sensitivity in detecting abnormal findings in each of the studies. The diagnostic findings in the dictated reports from the film and video readings were tabulated and compared to the expert panel findings to determine sensitivity for each observer for each viewing modality. The abnormal findings were subdivided into two categories; namely, all abnormal findings and secondly, the clinically significant abnormal findings pertinent to patient management. In addition, false-positive diagnostic findings were tabulated and analyzed. For each abnormal diagnostic finding as listed in the impression, readers provided a subjective confidence level on a rating scale between 1 and 10, with 10 being the most confident. Differences in readers' sensitivity in reporting both clinically significant and incidental diagnostic findings were compared using the paired two-tailed student T Test for analysis of discrete data sets. Subjective confidence levels were compared using Chi-Square analysis.

The film and video reading sessions were analyzed for time involved in image analysis and dictation for each reader. Image analysis time was from the reading of "indication for study" until the beginning of dictation. Dictation time was from the beginning of the audio dictation until completion. Each observer continued image analysis during dictation. For the video reading sessions, the number of screen changes, window level changes, review time for reanalyzing a previous study when

reporting the current examination and time required to write pertinent diagnostic impressions before completion of image analyses was recorded. Screen changes recorded two events: a) changing from the 16/1 format to 4/1 format, and b) paging through an examination using either screen display format. Each individual was also assessed for overall approach to diagnosis from the electronic workstation, specifically whether 256² resolution with 16/1 display format was used or whether a combination of 256² and 512² resolution with 16/1 and 4/1 display format was used.

At the end of the study, each reader was interviewed to obtain subjective impressions on the presence or absence of flicker and mental or eye fatigue, ease of comparison using the film and video display systems and what additional improvements each reader might consider for the electronic workstation.

Results:

The sensitivity of all readers improved when reporting from the film panel alternator as compared to reporting from the two-screen workstation (Table I). The improvement in sensitivity varied between 1 and 12%. For all positive findings, the improvement in sensitivity varied between 3 and 12% and for significant findings between 0 and 8%. The difference in sensitivity between film and video reading was significant at a P value ($\leq$) 0.05.

TABLE I
SENSITIVITY

RADIOLOGIST	VIDEO	FILM
A	84 (91)	96 (98)
B	79 (84)	82 (90)
C	74 (81)	82 (85)
D	76 (85)	80 (85)

() Significant Findings Only

TABLE II
VIDEO READING

	A	B	C	D
NO. OF SCREEN CHANGES	2.63	17.28	9.77	9.55
NO. OF W/L CHANGES	3.20	2.50	2.00	7.86
PREVIOUS STUDY REVIEW (MINUTES)	.08	2.75	1.14	1.29
NOTE WRITING (MINUTES)	----	.03	----	.09
ANALYSIS (MINUTES)	2.37	7.17	3.67	3.67
DICTION (MINUTES)	2.04	2.31	2.70	2.70
TOTAL (MINUTES)	4.41	9.48	6.37	6.37

All readers had an improvement in subjective confidence level when reporting from film as compared to the two-screen video console. However, this improvement was significant, as analyzed by the Chi-Square test, only for Reader A.

Pertinent findings which were missed on the video display but diagnosed from the film display included pericardial effusion in a patient with recurrent breast carcinoma (missed by one observer) and a 3 cm soft tissue lesion adjacent to the left piriformis muscle in a patient with a primary rectal carcinoma (missed by one observer). Pertinent findings which were missed on both the video and film display included a cecal carcinoma in a patient with multifocal hepatic lesions (missed by one observer), left adrenal enlargement in a patient with melanoma (two observers), left adrenal mass in a patient with carcinoma of the lung (one observer) and cirrhosis in a patient with abdominal aortic aneurysm and aortic dissection (two observers). An incidental finding which was missed by all observers on both video and film display was a subscapular lipoma in a patient with a history of malignant fibrous histiocytoma and a small pulmonary nodule.

There were nine false-positive observations, only one of which was made by more than one observer. Four false-positive observations were made on both the video and film display and the other five only from the video

display. For each viewing modality, there was a total of 120 separate study reports (30 study reports - 20 cases, 10 of which had comparison examinations - and 4 readers) containing 160 true-positive observations. Only one false-positive finding, (pneumoperitoneum from blunt abdominal trauma), which was made from the video display would have altered patient management.

There were marked differences in analysis time when comparing the film and video reading formats (Table II). The average analysis time for film reading was 2.56 minutes (range 1.62 to 4.42 minutes) and for video reading 4.22 minutes (range 2.37 to 7.17 minutes). Reader A was the fastest film analyzer (1.62 minutes) and also the fastest video analyzer (2.37 minutes). Conversely, Reader B was the slowest film analyzer (4.47 minutes) and also the slowest video analyzer (7.17 minutes). Reader A reviewed all video cases at 256^2 resolution only (16/1 display format) with minimal screen changes. Reader A did not use visual side-by-side comparison with the split screen mode when comparing two CT studies done at different times. Readers C and D reviewed all video cases at 256^2 and subsequently 512^2 resolution (4/1 display format). Average analysis time was 3.67 minutes. A proportion of this analysis time involved use of the split screen mode for visual comparison of CT images when comparing two CT studies. If the cases were analyzed in a very detailed fashion by review at 256^2 and subsequently 512^2 resolution and paging forwards and backwards through an individual case using the 512^2 format, total analysis time increased proportionately as evidenced by Reader B (7.17 minutes).

Except for Reader D, dictation time for film reading and video reading was comparable. Average dictation time for film reading was 2.51 minutes and for video reading 2.70 minutes.

Total analysis and dictation time for film reading averaged 5.07 minutes (range 3.92 - 7.37 minutes) and for video reading averaged 6.66 minutes (range 4.41 - 9.48 minutes).

For all readers, there was decrease in efficiency when reading from the video display versus the film display. This decrease, as a percentage of the total reading time for film reading was 13% for Reader A, 29% for Reader B, 19% for Reader C and 70% for Reader D. Reader D had the shortest total reading time for film reading (3.75 minutes per case), explaining the greater

percentage decrease in efficiency of this particular reader. However, Reader D was intermediate in efficiency in reading from the two-screen video display (6.37 minutes per case).

Discussion:

For all readers, lesion detectability was inferior when reading from the film two-screen video console as compared to the film panel alternator. This improvement ranged from 3-12% for all abnormal findings and between 0-8% for significant abnormal findings and was statistically significant. False-positive observations were rare for all readers. The minimal false-positive observations probably relate to study design in that each observer was provided with a pertinent clinical history consistent with the abnormalities present on each of the CT studies.

Reader A was the fastest reader from video and film. This reader consistently used only the low resolution mode of the video display (256^2 resolution - 16/1 format). Somewhat paradoxically, this reader also was the most accurate reader from the video display both for all abnormal findings as well as clinically significant abnormal findings. However, this reader also had the greatest percentage improvement in lesion detectability when comparing video reading to film reading. Reader A's improvement in accuracy appears more directly related to image resolution limitations of the 256^2 Matrix presentation. The other three readers routinely evaluated CT studies at the video console by initially surveying each case using 256^2 Matrix (16/1 display format) and then subsequently re-reviewing each case using the 512^2 Matrix (4/1 display format). For these three observers, failure to record positive abnormal findings probably relates to either failure to detect these abnormalities on the video and/or film display or perhaps failure to memorize the abnormality while dictating the case as another segment of the anatomy was displayed on the video screen. The lower luminance of the video display in comparison to the film panel alternator¹⁴ as well as minimal flicker in the video display could also have affected the results.

Reader A, using the 16/1 display format was able to view 32 images simultaneously from the two-screen video workstation and it is not surprising that Reader A had the shortest video reading time and the least percentage increase in reading time in comparison to the film panel alternator. For readers B, C and D, the major component

of the increased analysis time for video readings was the greater number of screen changes, predominantly paging through studies using the 4/1 screen display format. Reader D used many more window width and window level changes than the other three readers, though this instantaneous on-off function did not result in increased analysis time.

This study indicates that for all readers sensitivity and efficiency in reading from the video display station were inferior to reading from the film panel alternator. The individual differences between readers also demonstrate individual variation that affects the performance evaluation of these viewing modalities. Reader A who presumably has better perception and memory than the other readers performed better at the video display than some of the other readers on the film display. Nevertheless, Reader's A performance when reading from the film panel alternator was still better than when reading from the video display. All readers were unanimous in suggesting that for complex body CT cases an electronic display station would be improved by using four screens rather than two. All readers would prefer a higher resolution video display (e.g. 2048 x 2048 or 2048 x 1500), but for the 19" screen size used in this study suggested a 12/1 display format at 512² matrix would be preferable. Use of the 12/1 display format would maintain image size comparable to that currently utilized for multiformat film recording. All readers, including reader A, felt that image resolution using the 256² matrix is a limitation. Readers indicated that it is more difficult to remember perceived abnormalities while dictating if the appropriate images are not on the display while the dictation is being performed. The subjective feeling of mental and eye fatigue appeared directly related to the total analysis time for reading the video display. When exam comparisons were made, all readers indicated that this was performed better with film rather than the video display as 96 images could be displayed simultaneously on a film panel alternator and only 32 (16 per individual study) on the split screen video display.

A workstation linked to CT/MRI imaging systems has the potential to allow one radiologist to simultaneously monitor more than one imaging system and to dictate complex cases "on-line." We do not feel that our prototype system allows radiologists to dictate complex body CT cases with sufficient accuracy and prefer to use

the conventional film panel display for this purpose. Improvements in faster image display writing time, and total number of images displayed at full resolution should be beneficial. In essence, what these radiologists seemed to want for body CT reporting is an electronic workstation that simulates a film panel alternator as closely as possible. The alternative option, which was not evaluated in this study, would be to provide radiologists with a visual cue using miniaturized reference images that would be available as a "memory refresh" during dictation if the complete study could not be displayed at full resolution.

We plan to carry out a similar study using Magnetic Resonance case studies as images can be displayed at full resolution using the 16/1 display format. Although there are lesser requirements for display resolution for MRI as compared to CT, there are also a greater number of images per study.

In the future, it is likely that an appropriately designed electronic workstation linked to more than one imaging system could replace the physician viewing consoles of those imaging systems and could allow radiologists to improve efficiency by the use of on-line dictation from these devices. However, improvements in operational performance, as suggested by this study would seem necessary before this could be a practical implementation for complex body CT cases.

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First Phase of the Dutch PACS Project (1986-1989): Research Outcomes and Clinical Evaluation Results

Fenno P. Ottes, Albert R. Bakker and Jef M.L. Kouwenberg

BAZIS, Central Development & Support Group Hospital
Information System, Leiden, THE NETHERLANDS

Bart M. ter Haar Romeny

Radiology Department, Utrecht University Hospital
Utrecht, THE NETHERLANDS

ABSTRACT

In the period from 1986-1989 a PACS project has been carried out in the Netherlands. It comprised research, software development and clinical evaluation of a prototype PACS. The project was jointly performed by:

- the Utrecht University Hospital (UUH),
- BAZIS, Central Development and Support Group HIS, Leiden, and
- Philips Netherlands/Philips International product division Medical Systems.

The research and development activities were conducted by the UUH and BAZIS and funded by the Netherlands Ministry of Health Care. The prototype PACS system was provided and maintained by Philips.

This paper concisely reports on the activities in this project, and the results obtained. The major conclusion is that the implementation of a PACS can improve the logistics of the diagnostic image process in a hospital. It has been shown to be essential for the successful operation of a PACS, to couple it with the existing HIS, that must contain certain image related subsystems, e.g. an RIS. Simulation promises to be a good tool to support the design of the PACS architecture. Furthermore, diagnostic image quality of the prototype must be improved to be able to use it for primary diagnosis.

Based on a calculation of the costs of the prototype it has been estimated that hospital-wide PACS in the UUH would at this moment be much more expensive than the existing film-based system. In future however PACS costs can be expected to decrease. Concrete recommendations for future PACS implementation research are stated based on our experiences in this project.

The project is described in full detail in the, recently completed, 140-page concluding report [1].

INTRODUCTION

Shortly after the introduction of the optical disk technique the first PACS research project in the Netherlands was started in the early eighties. This pilot study on Image Storage Management was conducted by BAZIS and subsidized by the Dutch Ministry of Health Care.

This research led to the set-up of a grant proposal for the on-hand PACS research project by UUH, BAZIS and Philips. The target of this applicability study was to obtain more insight into the clinical aspects of PACS. The study was focussed on the potential benefits and how PACS should be implemented to obtain these benefits.

A multi-disciplinary approach is advisable to overcome the complexity of the PACS concept. The expertise from various disciplines should be combined and the partners should mutually stimulate each other:

- A hospital should provide the clinical test bed and the knowledge on the diagnostic process needed to perform a PACS prototype evaluation.
- An industry should furnish the PACS equipment. It should also allow feedback of the study results to the product development.
- A research group, that knows the information requirements in a hospital and is independent from the PACS vendors, is able to conduct an independent evaluation of the PACS system performance in a clinical environment. The obvious disadvantages of a blunt technology push can be avoided in this way.
- A coupling with the existing HIS should be realized.

To establish an optimal contact with the Dutch radiologists in general the Dutch Society of Radiodiagnostics was invited to closely follow all phases of the project.

The main objective of the Dutch PACS project was, as mentioned in the grant proposal: *to achieve a presentation of images coupled with related patient data, that allows the radiologist (and the requesting physician) to perform flexible, fast and fruitful diagnostic work.*

The various activities that were conducted are:

- Coupling and integration of the Philips prototype and the BAZIS HIS,
- Modelling and simulation of PACS hardware and its use in the hospital,
- Diagnostic image quality evaluation,
- Technical evaluation of the prototype PACS,
- Evaluation of the PACS coupled with the HIS used in clinical routine,
- Cost and benefit study of the prototype and for a whole hospital.

These studies are described in the next section.

The research partners can be characterized as follows:

- The University Hospital Utrecht is a teaching hospital with 900 beds, 3500 employees and 110,000 radiological examinations per year. Almost all imaging modalities are available: MR, CT, DSA, US and NM. The BAZIS HIS with about 800 connected terminals, is installed in the UUH. Until July 1989 the UUH was housed in a conglomerate of old free-standing buildings in the center of Utrecht. At that date it has been moved to a single new building at the periphery of the city.
- BAZIS develops and maintains the BAZIS HIS, an integrated hospital information system that contains 70 subsystems. The RIS subsystem is fully integrated with all other subsystems and includes reporting, appointment scheduling, and archive management and lending functions. The BAZIS HIS has been developed since 1972, and is currently used in more than 40 Dutch hospitals (together over 19,000 acute beds).

The proposal was accepted and funds were allocated to a total amount of fl. 4.4 million for the full 3-year project period.

ACTIVITIES AND RESULTS

The clinical evaluation took place primarily at one single ward (15 beds) of the Internal Medicine department. During the evaluation period, all relevant radiological images were provided in digital form for all patients at that ward. The patient related data were made available together with the images on the PACS workstation by means of a coupling between the HIS and the PACS.

COUPLING/INTEGRATION HIS/PACS

From the very beginning of the project it was recognized that a coupling between the prototype PACS and the existing HIS is necessary [2]. Many of the user demands concerning hospital data integration, PACS workstation functionality and PACS response times can only be met when such a coupling exists:

- for the identification of the images HIS patient data is required. The re-entry of this HIS information, and the errors that certainly will occur doing that, can be avoided by sending the data through the HIS-PACS coupling.
- together with the images related alphanumerical patient information from the HIS, including patient demographics and medical data like radiological reports and diagnoses, must be displayed on the PACS workstation in a coherent way.
- acceptable waiting times for PACS systems can with the current technology only be achieved when intelligent image management strategies are implemented. For example *prefetching*, i.e. to reduce waiting times images should be transferred from the slow archive to the fast workstation memory some time before the user actually requests to display these images. The image management system can be fed by HIS information, such as appointment and patient tracking data.

Actually a one-way PACS-HIS coupling was realized at the UUH. The record format of the messages was based on the ACR/NEMA standard. The message transfer was triggered by the registration in the HIS of certain events in the hospital. Such events were: admission, transfer or discharge of a patient, appointment made, changed or cancelled for a radiological examination, and authorization of a radiological report. The transferred information consisted of patient demographics and radiological history and radiological reports [3].

The coupling was first demonstrated during the 6th EuroPACS meeting that was organized in Utrecht and Leiden on April 25 and April 26, 1988, respectively. The coupling was in use during the full duration of the clinical evaluation (see section below). All transferred data has been logged and the log files have been used for analysis of the performance.

MODELLING AND SIMULATION

As we started the PACS project real-life experiments with hospital-wide PACS systems could not be performed. Such systems were not yet available and would be very expensive. Implementation of (hospital-wide) PACS should be well prepared, because mistakes in an early stage could lead to a large set-back in the development and implementation of PACS systems.

For these reasons, which are now still valid, we decided to use modeling and simulation in PACS research. By creating a model of the PACS combined with its hospital environment and by performing simulations of that model, the design of the PACS hardware can be supported. Also the adaptation of clinical working methods can be guided to allow an optimal implementation of PACS.

A simulation package, called MIRACLES (Medical Image Representation, Archiving and Communication Learned by Extensive Simulation) has been developed. This package has been used to analyze the performance of existing and imaginary PACS systems, including various models of the Philips PACS product line [4]. Simulation run results clearly demonstrated that prefetching is essential to be able to create PACS systems with acceptable waiting times.

DIAGNOSTIC IMAGE QUALITY and USER INTERFACE

A crucial condition for the acceptance of PACS by the radiologists is the diagnostic image quality of such systems. The commonly advocated method for evaluation of diagnostic accuracy is the observer performance study, that includes the Receiver Operating Characteristic (ROC) technique for the statistical data analysis.

A PC software package to support all phases of ROC studies has been developed. The package, which is called FEASIBLE (Feature Evaluation And System Inspection By Logged Experiments), allows the user to perform ROC studies in an easy and controlled way. It aids in the design of the experiment as a whole, in the execution of the psychophysical sessions and in the calculation of the ROC curves. Figures ready for publication, that contain multiple ROC curves, can be plotted with the package. The package has been sent, upon request, to over 25 interested research groups.

The applications of FEASIBLE include evaluations of the Philips prototype. It has been studied whether the diagnosis, based on an image digitized with the laser scanner and presented on a monitor of the Philips workstation, has the same quality as a diagnosis based on the original film viewed on a light box. The result largely depends on the kind of images that are used. For thorax phantoms and clinical mammograms it was shown that the image quality of the PACS system applied in the project is insufficient. For clinical head CT's no significant difference was detected [5].

Another important issue for the radiologist's acceptance of PACS is the human interface of the image workstation. Software for the retrieval, the display, and the manipulation of radiodiagnostic images on an image workstation based on general purpose hardware has been developed [6]. This package, called FRACTALS (Filmless Radiology and Computerized Task Analysis Lab Software), has been applied in research on image enhancement methods. The built-in journalizing facility of FRACTALS was used to track the user operations in a comparative investigation of the user-friendliness of two human-interface devices, i.e. a mouse and the dials.

TECHNICAL EVALUATION

The technical evaluation of the Philips prototype was started without delay after its installation in the dedicated digital reading room. Immediately major shortcomings became clear concerning the image matrix size, the reliability, the performance and the facilities for evaluation.

The video scanner showed to have a bad image quality. Philips replaced it on request with a laser scanner. Only one single matrix size, 1024x1024x8bits, was supported by the system. The ROC studies showed that the image quality obtained with this matrix was insufficient for primary diagnosis for various types of images. This implied that the clinical evaluation (see next section) could not be performed in the Radiology department and was thus restricted to the referring departments. The planned 1-screen workstation in the Internal Medicine ward was replaced by a 4-screen workstation in response to the urgent appeal of this department.

The system performance of the prototype appeared to be very limited. The network transfer rate was too low. The image management system did not support prefetching.

There were no facilities for data security and data base integrity. The clinical evaluation study and the performance research were further hampered because of the lack of logging facilities on the prototype.

Suggested improvements were, in contrast to earlier commitments, not realized because Philips discontinued the product line of the PACS prototype.

CLINICAL EVALUATION

The prototype PACS was implemented at one single ward (15 beds) of the Internal Medicine department. During the evaluation period, from October 1988 until July 1989 (when the hospital moved to the new building) all old and new radiological images were supplied in digital form for all patients at that ward by means of the prototype PACS. Utilizing the HIS-PACS coupling it was possible to provide patient history and radiological reports together with the images. All radiographs were entered into the system through digitization with the laser scanner. This process appeared to be rather cumbersome and thus manpower consuming.

The logistic process of diagnostic image distribution was analyzed for the film based system and using PACS. When films were used it appeared that about 25% was not available in the central archive. Measurements showed that it takes about 1.5 days on average extra to retrieve these hard to trace images from their actual location. In the PACS situation this could be reduced to a few hours [7].

The initial skepticism of the Internal Medicine physicians turned into a growing enthusiasm about the functionality of the PACS prototype. They particularly appreciated the availability of the relevant patient data - images and related alphanumerical information - so soon after the acquisition. Also the certainty that the images were present, and accessible 24 hours per day contributed to the physicians' satisfaction.

TECHNOLOGY ASSESSMENT

Technology Assessment appeared to be a rather broad issue. Here we focussed on the financial aspects, i.e. costs and savings, of PACS implementation in a dutch hospital.

The total costs of the prototype PACS have been calculated based on prices provided by Philips-AT&T. By extrapolating these costs to the full UUH it can be predicted that PACS is at present much more expensive than the conventional system. The outcomes of similar studies in the literature differ enormously. This clearly indicates the need for an international dialogue on the issue.

A PC software package has been developed to calculate first year costs of the PACS system versus the conventional film based system. The CAPACITY (Cost/critical Analysis of Picture Archiving and Communication Indicating its True Yield) package is based on three models: a model of the PACS, one of the hospital workload, and one of the price trend of each cost component. CAPACITY has been sent upon request to 10 research groups. The dissemination of CAPACITY has already proven to enhance the international dialogue.

The results of CAPACITY based on the UUH figures predict that the break-even point will occur near the end of this century. A sensitivity analysis indicates that the costs of PACS largely depends on the required number of workstations and Computer Radiography systems, and the prices of these components [8].

The clinical evaluation also suggested that PACS will cause a reduction in length of patient stay. Whether such a reduction will lead to savings on the hospital budget depends on the country's reimbursement system.

RECOMMENDATIONS FOR FUTURE RESEARCH

The strategy for PACS in near future should not aim at hospital-wide PACS but at partial PACS. The subdivision can be realized along two dimensions. Firstly, instead of all departments only a few could implement PACS. Secondly, not all types of images are treated digitally, but either the digital modalities or the conventional projection roentgen images are included in the PACS. This implies that film has still largely to be used in parallel with digital images.

From our PACS project we learned that the major technical requirements for PACS are:

- sufficient image quality for primary diagnosis,
- a user-interface, that allows an acceptable fast way of working,
- an intelligent image management system, that includes prefetching,
- a bi-directional coupling,
- software logging facilities.

Some hospitals and/or departements will benefit more from PACS than others. For example intensive care will have a great advantage from fast image delivery. A hospital with a spread-out floor plan will benefit more from PACS, because films do no longer have to be transported over the long distances.

Research should include the following issues:

- The effects on the working methods of the radiologist and on the organization of the Radiology department.
- Modelling and simulation to support the hardware design and to guide the implementation. Also the development of software, such as image management strategies can be aided by simulation.
- The diagnostic image quality of the new generation of PACS.
- The user-interface of image workstations and the facilities for e.g. navigation through all images in a study.
- Development of further integration of PACS with the hospital information system environment.

- Structure and organization of the PACS data base system, including image management strategies.
- Technology Assessment of PACS at various scales, e.g. per department, per hospital, nation wide.

An extremely important tool for PACS research, in particular for clinical evaluation and performance studies, is a facility in the PACS system under study for the logging of all user operations and of the load of all components.

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Soft Copy Interpretation of Portable Chest Radiographs

G. James Blaine, R. Gilbert Jost, Stephen M. Moore, et al

Mallinckrodt Institute of Radiology, St. Louis, MO

ABSTRACT

Computed Radiology has been used routinely at the Mallinckrodt Institute for portable radiographs for over two years, although film has consistently been used as the medium for interpretation. We have recently set out to explore the feasibility of using electronic displays for both primary and secondary interpretation of portable chest radiographs. A prototype medical image presentation system supports a workstation-based user interface integrated with high-performance auxiliary displays. High-resolution displays allow for primary (using 2000 x 2500 pixels) and secondary (using 1000 x 1000 pixels) interpretation. The user interface facilitates case selection and access to patient information including radiology reports. Digital images are acquired directly from the CR unit and spooled to the review stations for interpretation. Experience with these prototype systems will be reported.

Artifacts Introduced by Laser Scanner Digitization of Radiographs

Ethan J. Halpern, Peter D. Esser, Edward Nickoloff, et al

Columbia Presbyterian Medical Center, Columbia University,
New York, NY

Introduction

Laser film scanners are commonly used to digitize plain radiographs for teleradiology and picture archival and communications systems (PACS). Laser scanners provide digital images of higher quality than those obtained by digitizing analog signals from a video camera. These scanners, however, may introduce new types of artifacts into the digital images.

Many phantoms are available for testing various aspects of image quality for CT, MR and commercial video systems. We have recently described a quality control phantom for the digitization of radiographs[1] which was designed to test several parameters of image quality, including resolution, low contrast discrimination, gray scale response, high frequency noise, and geometric distortion.

Quality control protocols that focus on general parameters of image quality may not identify clinically important artifacts introduced by a specific imaging modality. In this paper we describe several artifacts which have been introduced into images by a commercial digital radiography system using a laser film scanner. A complete quality control protocol for digital radiology should incorporate an active search for these and other similar artifacts as an adjunct to the quantification of general parameters of image quality.

Materials and Method

A copy of the Society of Motion Picture and Television Engineers (SMPTE) test pattern[2] created on a 3M laser printer was obtained from the 3M Medical Imaging Systems Division (West Coldly, NJ).

Multiple film phantoms were constructed by exposing commercially available line pair phantoms (Nuclear Associates, Carlo Place, NY) directly to film. These films were exposed at 50 kVp and 0.8 mass using a 0.6mm focal spot and a target to film distance of 56 inches. Physical phantoms were placed directly on the film cassette. No grid was used.

Commercially available optical density step tablets were used (DuPont; Wilmington, DE). Other optical density step tablets were creating by exposing film with a 21-step sensitometer (X-Rite; Grandville, MI). The optical densities on these films were measured with a model 301 densitometer (X-Rite).

The various phantoms described above as well as multiple clinical images were digitized on a CommView digital radiography system (AT&T Bell Laboratories, West Long Branch, NJ and Philip Medical Systems, Shelton, CT). This system uses a model FD2000 laser film scanner (Dupont) operating at 2048 x 1684 pixel resolution with 12 bits of data per pixel. During the period of this study, the CommView system was upgraded from the 1.0 software release with a results viewing station monitor to the 2.1 software release with an enhanced graphics station monitor.

Images were transferred to a personal computer workstation[3] and truncated to the most significant 8 bits. They were visually inspected using the roaming zoom and contrast enhancement features of the ImagePro software package (Media Cybernetics; Silver Spring, MD). Additional quantitative analysis was performed with custom developed software to calculate mean and standard deviation values with the original 12 bit data for various regions of interest.

Results

1) Streak artifacts

Digitized phantom images may contain streak artifacts from the edges of very light areas surrounded by dark regions. This artifact was frequently seen with the SMPTE pattern (figure 1A). The degree of streaking was noted to vary with the position of the SMPTE pattern within the image matrix. Similar streak artifacts were not found to be noticeable in clinical images.

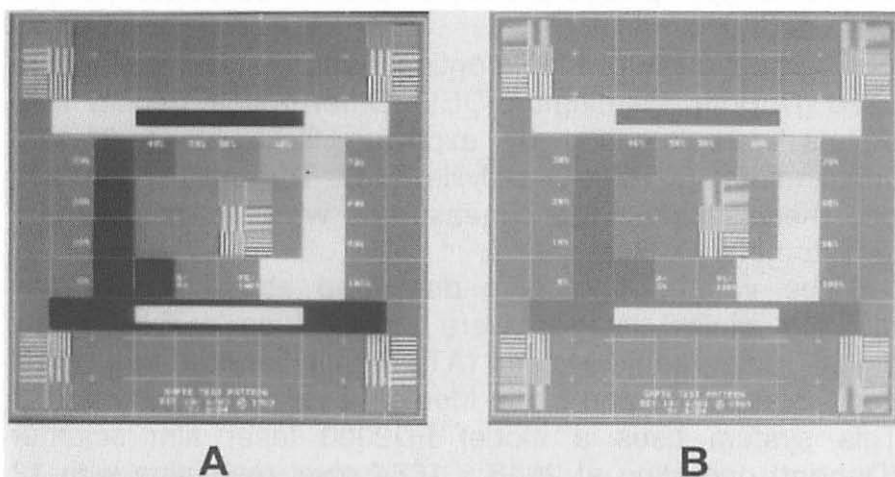


Figure 1. Two SMPTE patterns digitized from a single sheet of x-ray film. A corresponds to a pattern present on the upper half of the film. Streak artifacts are demonstrated at abrupt borders between bright and dark bars in the pattern. B was in the lower portion of the same film. Low contrast definition is degraded as compared to the image in A.

2) Local variation in gray scale response

Brightness and contrast may vary from point to point within a digitized image. For example, the two images displayed in figure 1 were obtained by simultaneously digitizing two identical SMPTE patterns from a single sheet of film. Nonetheless, there is a marked difference in both the

brightness and contrast of the two images. This artifact led to the discovery of a light leak in the laser scanner which was subsequently corrected. In addition, we have documented a consistent, though not visually perceptible, difference in the digital values assigned to various optical densities on the left and right sides of the image.

3) Linear Artifacts

Various types of linear artifacts may be introduced by either the laser scanner itself or by the software interface which transfers the image data into the PACS data base. Images obtained with the initial 1.0 software release of the CommView system demonstrated a linear artifact through the center of each image (figure 2). The appearance of this artifact varied with the contents of the phantom images.

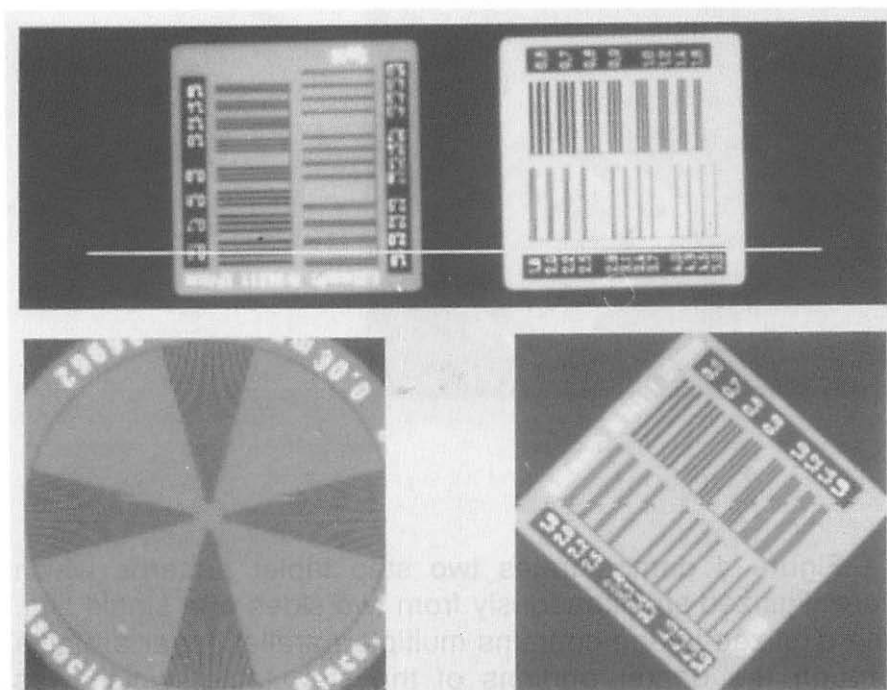


Figure 2. Linear artifacts introduced by the digitization of plain film phantoms. The appearance of the artifact varies with the phantom.

However, it was not appreciated on digitized clinical images. This particular artifact was not present after the system was upgraded to the 2.0 software release. The cause of this artifact was never determined, but was probably related to a software error in transferring data from the laser scanner.

Other linear artifacts may be related to the actual hardware within the laser scanner. Figure 3 demonstrates a curvilinear dark line which was noted in the upper right corner of multiple phantom and clinical images. This artifact was corrected by replacing a scratched glass plate in the laser scanner.

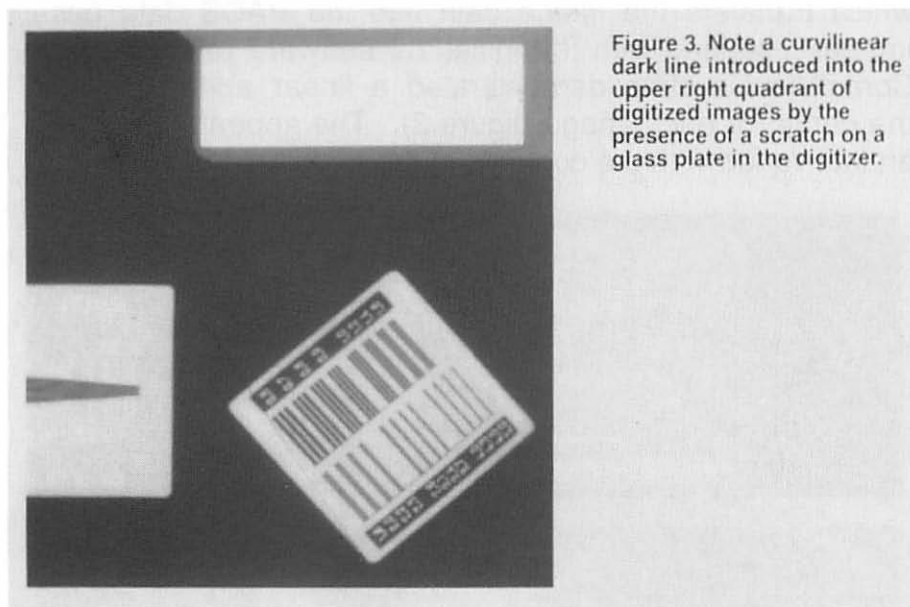


Figure 3. Note a curvilinear dark line introduced into the upper right quadrant of digitized images by the presence of a scratch on a glass plate in the digitizer.

Figure 4 demonstrates two step tablet patterns which were digitized simultaneously from two sides of a single film. The digitized image contains multiple parallel linear artifacts through the darker portions of the step tablet which was present on the left side of the film. No such artifact is noted from the right edge of the film. Similar linear artifacts are present at the left border of clinical images.

A

1	1.19
2	2.19
3	3.20
4	4.22
5	5.25
6	6.31
7	7.40
8	8.53
9	9.78
10	10.99
11	11.49
12	12.92
13	13.34
14	14.68
15	15.96
16	16.31
17	17.323
18	18.330
19	19.334
20	20.338
21	21.340

B

1	1.19
2	2.20
3	3.21
4	4.23
5	5.26
6	6.32
7	7.41
8	8.55
9	9.81
10	10.15
11	11.53
12	12.99
13	13.40
14	14.72
15	15.99
16	16.31
17	17.325
18	18.331
19	19.336
20	20.340
21	21.341

Figure 4. Step tablet patterns following digitization. The images have been reoriented to facilitate comparison.

A. Pattern on the right edge of the original x-ray film. The digitized image reveals no linear artifacts.

B. Pattern on the left edge of the original film. Note the presence of linear artifacts in the darker portion of the step tablet.

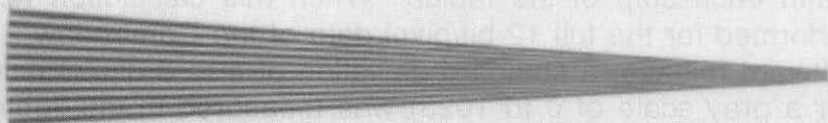
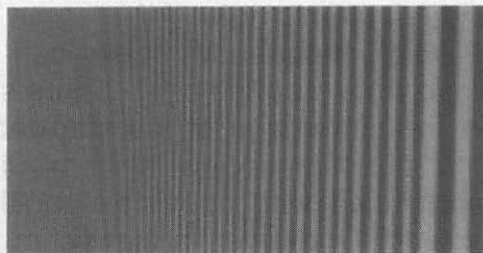
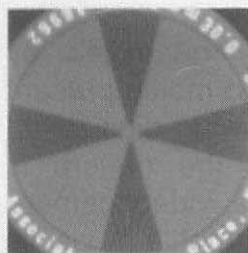


Figure 5. Moiré patterns are introduced into digital images when the line pair frequency approaches the sampling frequency of the digitizing device.

4) Sampling frequency artifact

This artifact is related to the resolving ability of the digitizing device, and will be present in all systems which digitize an analog image. Figure 5 demonstrates the Moire pattern which is seen when the line pair frequency of a phantom approaches the sampling frequency of the digitizing device. The appearance of the pattern varies with the orientation of the lines.

5) High frequency noise

High frequency noise in digital images may be visible as mottle. It is generally a greater problem in the darker regions of an image. Radiography systems that use a laser scanner to digitize images tend to have less of a problem with high frequency noise than the less expensive video camera based systems. Nonetheless, some high frequency noise will be introduced into the images by sampling error and "electronic noise"[4].

High frequency noise can be easily quantified by digitizing a step tablet[1]. There should be no mottle present on the film image of the step tablet. Following digitization with the CommView system (figure 6A), the pattern is reproduced with no visible mottle. With a video camera system[3], however, a significant amount of mottle is visible (figure 6B). High frequency noise was quantified by calculating the standard deviation of the digital pixel values within each step of the tablet. When this calculation was performed for the full 12 bit/pixel data of the CommView 2.1 software release, a standard deviation of 4 to 5 digital units (for a gray scale of 0 to 1023) was measured in the lighter steps (0.2 - 0.4 density units). In darker areas (3.0 - 3.4 density units) the standard deviation measured in the range of 60 to 100 digital units.

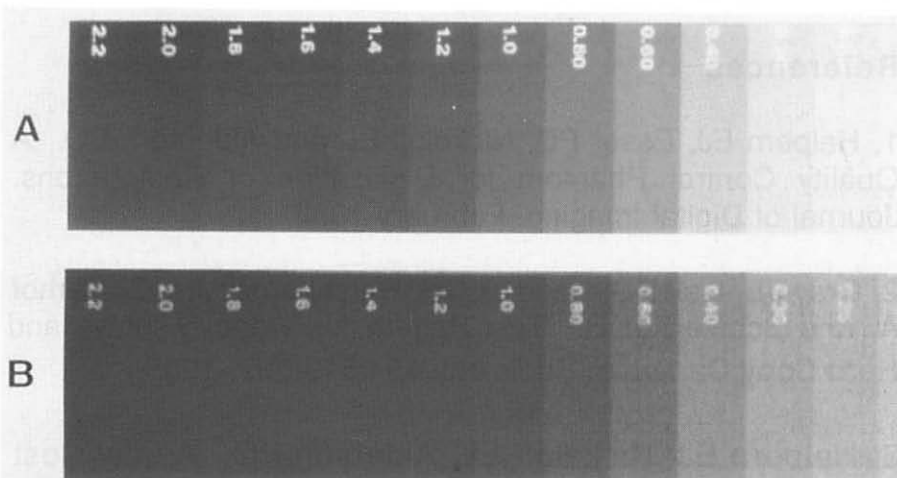


Figure 6. Digital images of photographic step tablets.
A was digitized with a laser scanner system. No noise is visibly detectable.
B was digitized with a video camera / frame grabber combination. A significant degree of mottle is present.

Discussion

A formal quality control protocol is essential to insure the diagnostic accuracy of any digital radiography system. Such a protocol should include regular inspection of digitized phantom images to quantify parameters of image quality. In addition, a small set of radiographs with specific clinical findings should be digitized and inspected on a regular basis. In this paper we have described several discrete classes of artifacts introduced by laser scanner digitization of radiographs. Familiarity with these specific artifacts may be helpful in the development of a quality assurance program for digital radiography.

Acknowledgement

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CCD Mammography

Tim B. Hunter, W.V. Schempp, Hans Roehrig, et al

Department of Radiology, University of Arizona Health Sciences Center,
Tucson, AZ

Charge-coupled devices (CCD's) have exquisite sensitivity to light in the visible and near infrared portions of the spectrum. They are the main imaging receptor used by professional astronomy and are finding extensive use in many other disciplines. CCD's are a potentially ideal receptor for mammography and other areas of diagnostic radiology because of their wide dynamic range, real-time image acquisition and display, and low patient dose. They suffer from small size and relatively low spatial resolution.

Experimental work has been performed with a LoRad mammography unit using a Trimax

8 screen coupled by a 50mm focal length f/2.0 lens to a Thomsom CSF TH7882 CCD. A mammographic phantom (CRIS Inc. model X1 1) served as a test object featuring both simulated high contrasts calcifications and low contrast nodules of different sizes.

The early phantom results are encouraging (figures one and two). At high magnifications the lens collects a sufficient amount of light for the image to be x-ray photon noise limited. Phantom images consistently have more dynamic range than comparable film screen images. Greatly increased contrast resolution can, in part, make up for more limited spatial resolution of the CCD system so that tiny calcifications are imaged rather well. CCD magnification views on the order of 3-4x compared to a standard film screen view show much more spatial detail (figures three & four), but have a very limited field size of about 5cm by 5cm. With optimum electronics

and optimum mammography screen-to-lens coupling, a CCD mammography system has the potential for reducing patient dose by a factor of ten.

We will soon begin patient studies to investigate CCD mammography for "real-time" needle localizations, magnification views and specimen radiography. Large, high resolution CCDs now entering the market offer the possibility for CCD use in everyday mammography in the not too distant future.

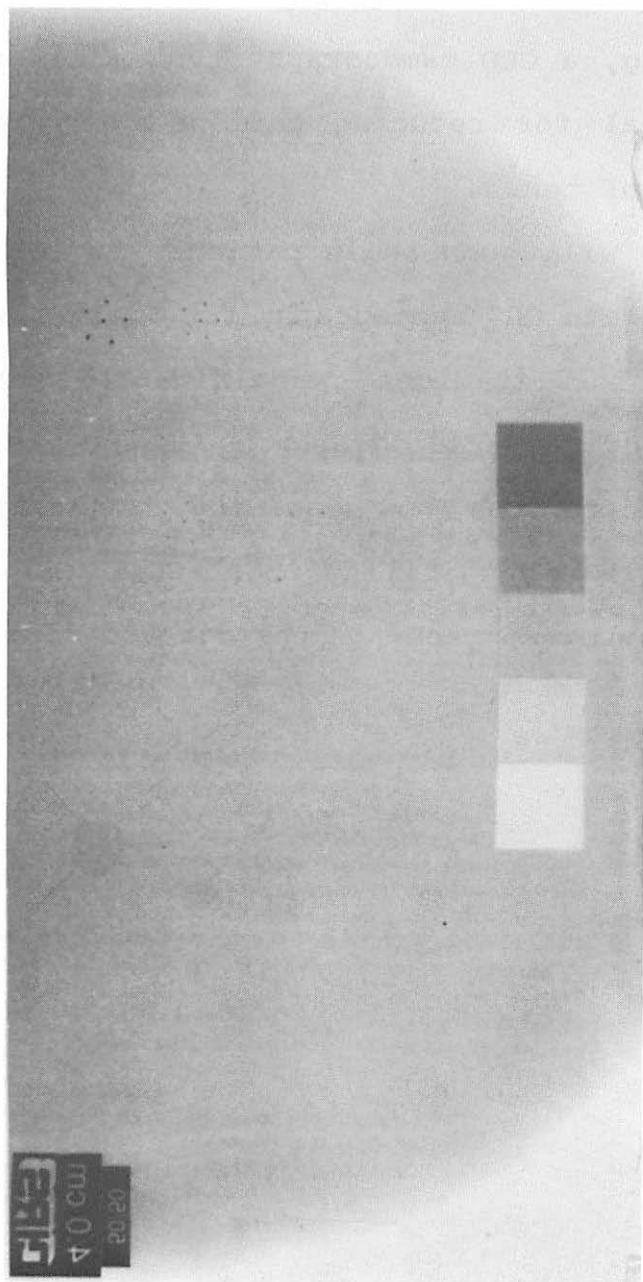


FIG. 1. Film/screen image of mammography phantom.

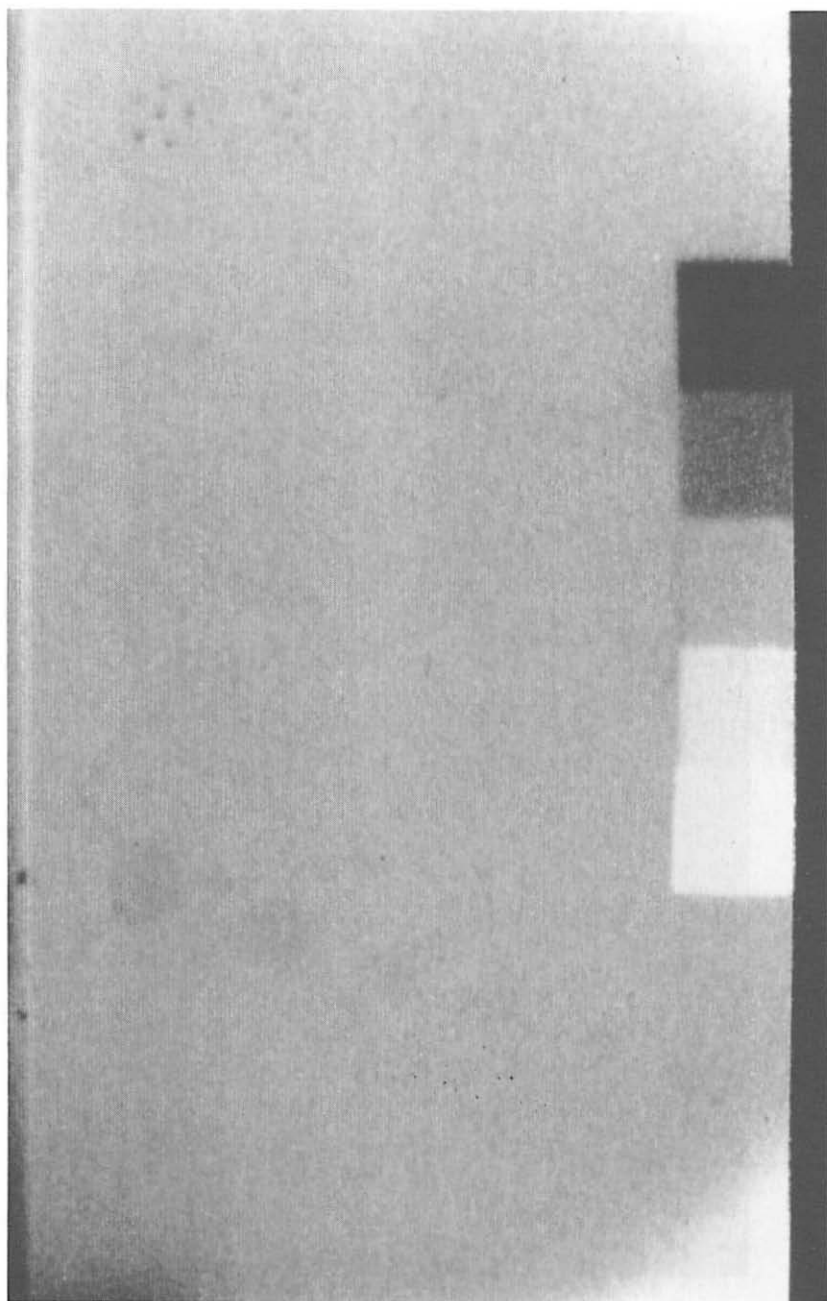


FIG. 2. CCD camera image of mammography phantom.

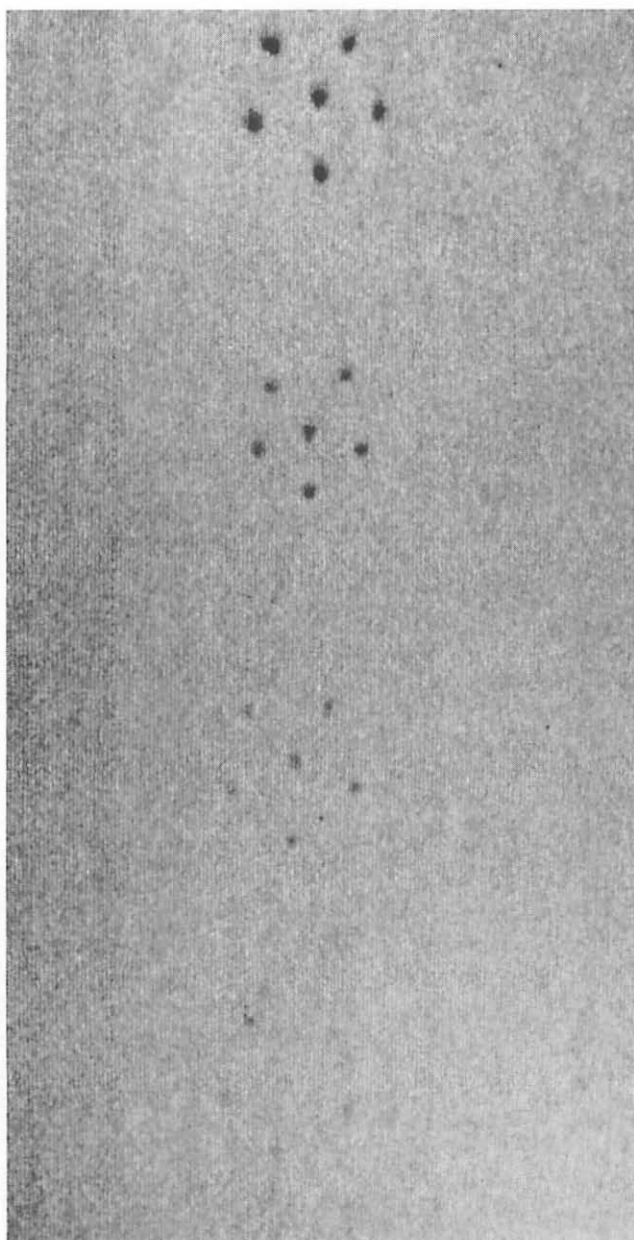


FIG. 3. CCD camera image of microcalcifications in mammography phantom.

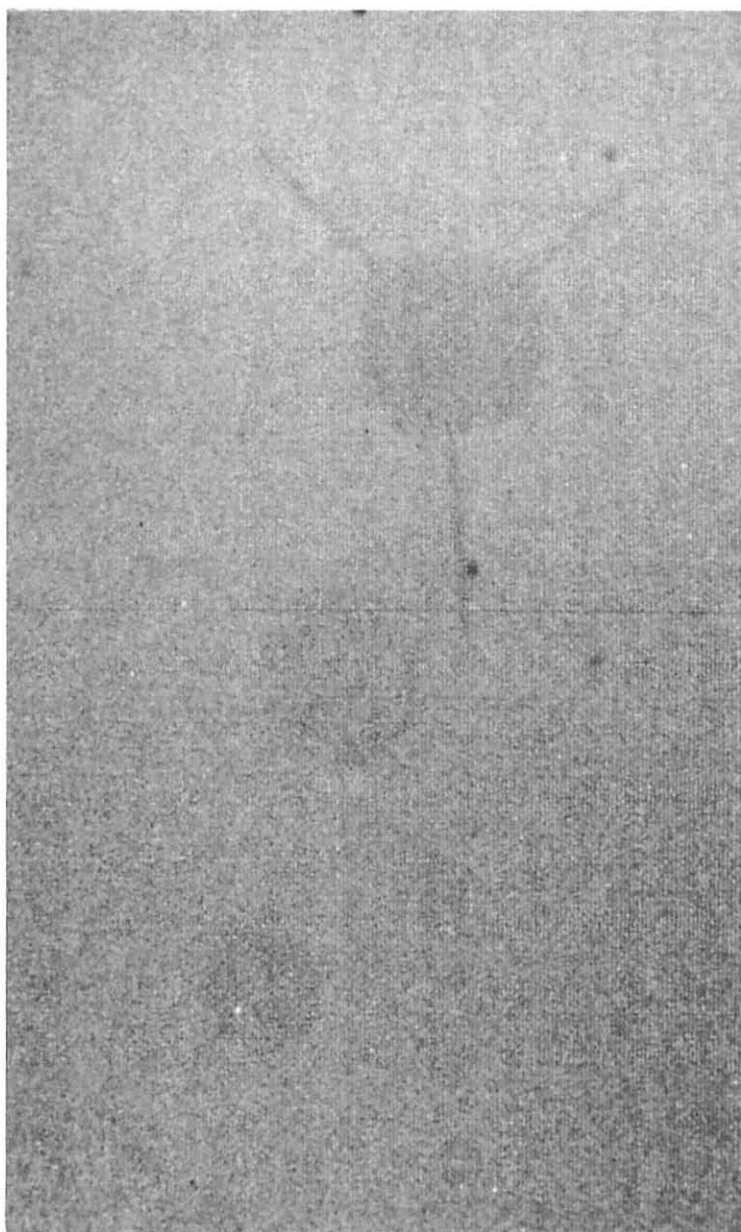


FIG. 4. CCD camera image of low contrast nodules of mammography phantom.

PACS Technical Workstation Design

Evaluation of Input Devices for "Selection" Tasks in Diagnostic Workstations

Kris Maloney, Kevin M. McNeill and John S. McNeill

Department of Radiology, University of Arizona, Tucson, AZ

George W. Seeley and William J. Dallas

Department of Radiology and Optical Sciences Center,
University of Arizona, Tucson, AZ

Abstract

A goal of the User Interface Study Group (UISG) at the University of Arizona is to determine the requirements of a successful user interface for digital radiology. In pursuit of this goal we have conducted an experiment to determine 1) what effect the input device has on the users performance, measured in time and accuracy, when using a digital workstation; and 2) if non-radiologists can participate in user interface studies that do not require diagnosis. Based on a model of the reading process, developed earlier by the UISG, a task was defined that required the same types of computer-human interaction as the reading process but did not require a diagnosis. Twenty observers, 4 radiologists and 16 non-radiologists, participated in this study. The results of this study indicate that the type of input device used has a significant impact on user performance, and that in tasks that do not require diagnosis non-radiologists may perform similarly to radiologists.

Introduction

The use of the digital workstation, in all radiologic modalities, as a tool for primary diagnosis is a critical factor determining the success of a complete PAC system. Many of the issues that will determine acceptance of the workstation involve the physical characteristics of the digital workstation (i.e. spatial and contrast resolution). These physical and perceptual requirements are being studied at the University of Arizona, as well as elsewhere, to determine what characteristics are necessary for a digital workstation to be used for radiologic reading.^{1,2}

Also critical for the digital workstation to be accepted as a tool for primary diagnosis is the transition of the radiologist from the current film based reading methods to the new digital technology. This is a major obstacle that must be overcome to realize the complete benefit of a PACS. This obstacle is particularly difficult to overcome because the current film based system works well for the radiologist and has become ingrained in the diagnostic process.³

In order for the digital workstation to replace film based reading methods the transition must occur with as little disruption as possible to the radiologists' learned

reading patterns. The radiologist must be able to read images without thinking about the computer.⁴ Research in other areas has shown that a poorly designed interface can cause degraded user productivity, user frustration, increased training costs, and the need to either redesign and reimplement the user interface or entirely replace the system.⁵ In the field of radiology, these types of problems can be disastrous. To effectively design a user interface that will be accepted and used by the radiologist it is necessary to understand the task which is to be performed by the radiologist.⁶ To better understand the radiologists' task we have formulated a model of the current film based reading methods.^{7, 8}

Model of the Reading Process

The reading model we selected to use in this experiment models the process for lightbox reading used for outpatient cases. The model was derived by analyzing video tape of six radiologists performing this type of reading. We chose this model because it describes a task that is very cumbersome and time consuming for the radiologist requiring significant direct manipulation of films. This model divides the reading process into three phases: Setup, Viewing/Diagnosis, and Wrap up. The following is an overview of the reading model.

- Setup
 - * get next case.
 - * get demographic information.
 - dictate case demographics.
- Viewing/Diagnosis
 - * get films from envelope and place on lightbox.
 - compare films.
 - dictate report.

- Wrap-up.

- * replace films in folder.
- write diagnosis synopsis on folder.
- * place folder on stack of completed readings.

Based on this film reading model we have further broken the reading process down into a series of elementary tasks and from this determined that most of the interaction by the radiologist with the film could be classified as "selection" tasks. Selection tasks are tasks where the user makes a selection from a set of alternatives (i.e. patient folder or desired film).⁹ Research in other areas has shown that one of the most important elements in the design of user interfaces is the choice of the devices and techniques by which the user performs elementary tasks.¹⁰

The tasks we determined to be completely classifiable as a selection task are marked with asterisk (*) above). The remaining tasks consist of selection tasks but may contain other types of elementary tasks. Because of the significance of the selection task in this type of reading process, we designed an experiment to determine if the input device used has an effect on the performance of the user while performing selection tasks at a digital workstation.

The Experiment

Goals

There were two main goals in this experiment.

The first, as mentioned above, was to determine if the choice of input device had an effect on the overall performance of the user.

The second goal of the experiment was to determine if, when given a specific non-diagnostic task, non-radiologists perform similarly to radiologists. Conducting

research into the elementary components and techniques used in a specific interface design, although proven successful, is very time consuming requiring a large number of users to participate frequently in testing and experimentation. In the design of a user interface for a digital workstation, the main requirement would be on the radiologists time. Adding non-radiologists to the user population would greatly relieve the burden on the radiologists.

Dependent Variable

The data collected in this experiment was measured in terms of the dependent variable, performance. In this experiment, performance was measured in two ways; 1) the time it took to complete the task and, 2) the number of errors that occurred when completing the task.

Independent Variables

There were three variables that we controlled and modified during the experiment.

The first, and most obvious, variable we controlled was the input device used to perform the specified task. The subjects were randomly and evenly assigned either the mouse or the touch screen as the input device to be used throughout the experiment.

The second variable we controlled during the experiment was complexity. The task was designed to include four complexity levels. The order in which the complexity levels were encountered and the amount of work required at each complexity level for each subject was constant throughout the experiment.

The third variable we controlled in this experiment was body position. To avoid biasing the results in favor of a particular input device because of body posi-

tioning we had each subject complete the required task twice; once in a sitting and one in a standing position. The subjects were randomly and evenly assigned to either stand first or sit first to avoid introducing a training effect to the body positioning results.

The Digital Workstation

This experiment was conducted on the Arizona Viewing Console (AVC), a digital workstation here at the University of Arizona Department of Radiology.¹¹ Input devices available on the workstation are three touch screen equipped monitors, one for command and the remaining two for image data; function knobs used for window, level, filter and continuous bilinear-interpolative zoom, a keyboard, trackball and a mouse.

The Task

We defined a task that involved the same type of activities as the film based reading model but that did not require diagnosis. The following is a discussion of the basic design of the experiment.

Throughout the entire experiment there were two command menus displayed on the command monitor. One menu contained the commands (HORIZONTAL, VERTICAL, BOTH, and RESET) that would be used to manipulate image orientation during the experiment, the other menu contained a list of folders and the NEXT key.

The basic task of the experiment was to manipulate the images in a series of 20 folders to match a predefined pattern of how the images should appear. To do this, the images in a folder were displayed on the left hand image monitor and a goal card representing the same set of images, but at different orientations, was shown to the subject. The subject was required to select an image from the folder. For the purpose

of this discussion, the term "select" can be defined as; touch the named object, in the cases where the touch screen was the assigned input device, or move the cursor to the object and depress the mouse button where the mouse was the assigned input device. Selecting the image from the folder on the left hand image monitor caused the image to be displayed on the right hand image monitor for manipulation. The subject then selected, from the menu on the command monitor, the type of manipulation, either HORIZONTAL (flip on the horizontal axis), VERTICAL (flip on the vertical axis), BOTH (flip on both the horizontal and vertical axis, and RESET (reset the orientation to the original orientation) required to make the image appear at the same orientation as the corresponding image on the goal card. The subject then selected the next image from the folder on the left hand image monitor and selected the appropriate type of image manipulation from the command monitor. When a new image was selected, the previously displayed image was updated in the folder display on the left hand monitor to include the manipulation. This process continued until the sub-

ject felt confident that all of the images displayed on the left hand image monitor matched the images on the card. The subject then selected NEXT from the command menu and moved on to the next folder.

The folders were ordered and displayed to the subject in increasing levels of complexity. For the purpose of this experiment we have defined complexity to be the number of images in a folder. The first five folders contained one image, the next five folders contained two images the next five contained three images and the last five folders contained four images.

To begin sixteen non-radiologists completed this task twice, once in a sitting position and once in a standing position to

result in 32 sets of data.

One person administered all of the experiments.

Results - Non-Radiologists

When measured at a 99% confidence level, the effect of the input device on user performance, for both time (Figure 1) and accuracy (Figure 2), for all complexity levels was statistically significant.

$$[F(1,124) = 43.58, P < .01]$$

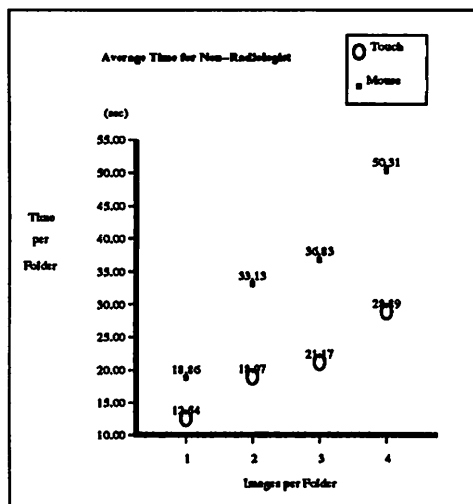


Figure 1. Average Times.

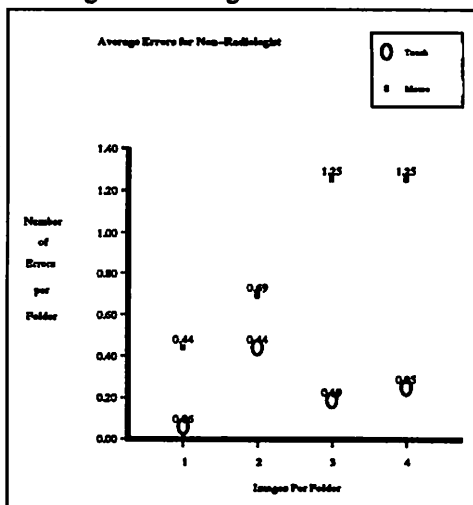


Figure 2. Average Errors

The body positioning had no statistical effect on user performance.

We also noticed a statistically significant training effect at a 99% confidence level between the first and second time the subject completed the defined task [$F(1,124)=7.15, P < .01$].

The Radiologists

We then added radiologists to the study. Analysis of data collected previously, from the experiments with the non-radiologists, had shown that body positioning did not effect the performance of the user. Because of this we decided it was unnecessary to have the radiologists perform the same task twice with the same input device. Instead we had each radiologist perform the specified task with both the mouse and the touch screen. The radiologists were assigned randomly and evenly to run either the mouse first and then the touch screen or the touch screen first and then the mouse.

Because of the constraints placed on the radiologists time the single experimenter who had conducted all of the non-radiologists experiments was not available to conduct the experiments for two of the radiologists. A second experimenter administered the experiments for these two radiologists. In analyzing the data we realized that this logistical problem had introduced a new variable to the experiment. All of the non-radiologists and two of the radiologists received coaching from the experimenter. This coaching occurred when the subject became confused by either the task or the user interface of the workstation. The same type of instruction was given to all of the subjects if they encountered a problem. The second person, conducting the experiment for two of the radiologists, did not provide the subjects with coaching of any type.

Upon completion of the experiment

each of the radiologists was asked if he or she felt the task accurately represented the "mechanics" of the film reading process. All of the radiologists felt that the task was a good representation of the film reading process.

Results - Including Radiologists

Figures 3 and 4 on the following page show the results of the experiments conducted with the four radiologists. Each radiologist is shown as a point of the graph with the radiologists who received coaching appearing as an open circle and the radiologists who did not receive coaching appearing as a closed triangle. The vertical bars (to the left of the points representing the radiologists) show the mean and standard deviation for the non-radiologists, for the first time they completed the task, with the mean represented as a black diamond and one standard deviation above and below the mean being shown as a horizontal bar.

Discussion

With the radiologists, as with the non-radiologists, the effect of the input device on user performance for all complexity levels and with and without coaching was statistically significant with a confidence level of 99%. Regardless of whether the mouse was used first or the touch screen was used first performance, measured in both time and accuracy, was significantly better when using the touch screen.

The general trend of the radiologists receiving the same type of coaching as non-radiologists seems to indicate that non-radiologists may behave similarly to radiologists when performing specific non-diagnostic tasks. Additional radiologists will be tested to verify this trend.

Although no statistical data can be inferred, coaching also had a major effect on the radiologists performance. Because of the significant performance advantage no-

ticed for radiologists receiving minimal coaching, questions arise regarding the need for intelligent and interactive help programs as part of the user interface for digital workstations. This area also requires additional study.

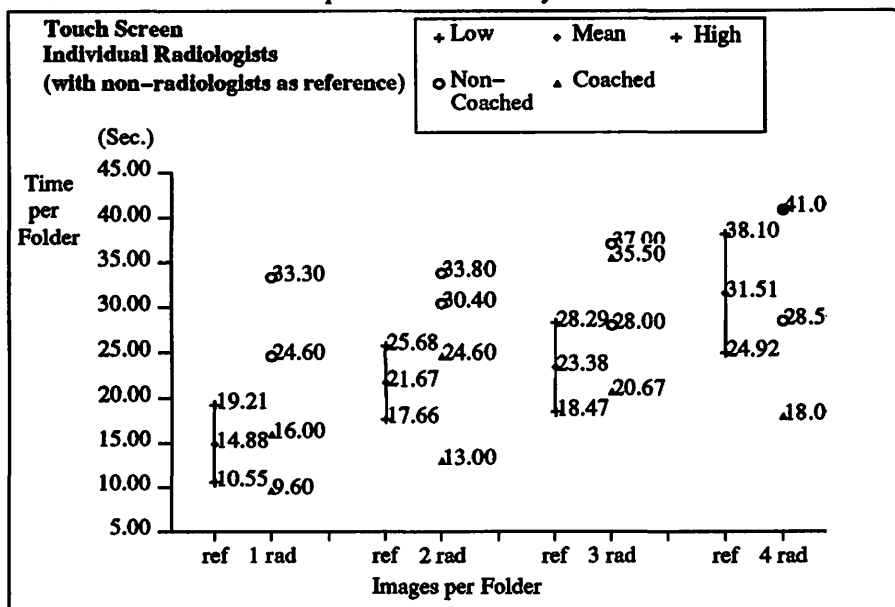


Figure 3. Radiologists' time plotted as points with non-radiologists' distribution - Touch

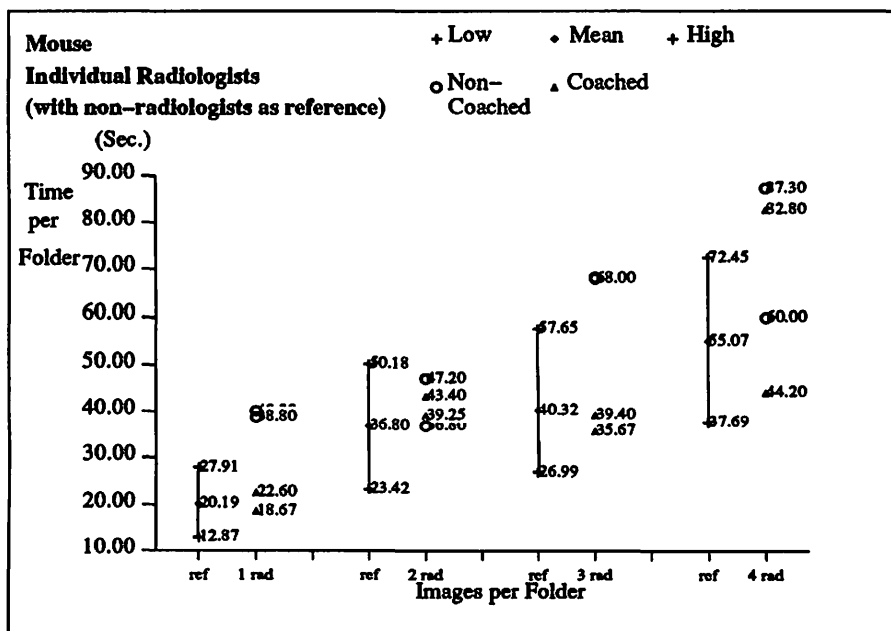


Figure 4. Radiologists' time plotted as points with non-radiologists' distribution - Mouse

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Perceptual and Physical Concerns When Displaying Images to Be Used in PAC/IMAC Investigations

George W. Seeley, Jannick Rolland, Jose Guillen, et al

Department of Radiology and Optical Sciences Center,
University of Arizona, Tucson, AZ

ABSTRACT

Future PAC/IMAC systems will be acquiring, transmitting, storing, and displaying a variety of digital images. Film images will also be digitized and incorporated onto the system. The process of displaying digital images is one of the most crucial parts of such systems. These digital images will be displayed either on film or electronically. Much research is now being done to define the needs of these display systems. One of the ways researchers investigate the needs of PAC/IMAC display systems is to acquire a set of clinical images and digitize them. The resultant digital images are then manipulated in some way and then either written back to film or displayed on an electronic monitor. Reading performance for the original set and the duplicates are then compared using the receiver operating characteristic (ROC) experimental paradigm. For the results of these experiments to be interpreted properly the displaying of the digital image must be controlled such that they are matched as closely as possible to the original film images except for the variable(s) under study. This paper will describe some of the work being conducted at the University of Arizona Radiology Department for controlling CRTs and laser writers to conduct these type studies.

INTRODUCTION

A large amount of psychophysical/clinical research is now being conducted to investigate the needs of PAC/IMAC systems [1-4]. The questions being investigated have become more and more subtle over time as we learn more about what is needed. Thus, the need to control the experimental environment becomes even more pertinent. One of the ways researchers investigate the needs of PAC/IMAC display systems is to acquire a set of clinical images and digitize them. The resultant digital images are then manipulated in some way and then either written back to film or displayed on an electronic monitor. The original set and the duplicates are then compared using ROC analysis. For the results of these experiments to be interpreted properly the displaying of the digital image must be controlled such that they are matched as closely as possible to the original film images except for the variable under investigation.

For example, if an experimenter wants to define whether the spatial resolution of a CRT display is sufficient for making diagnosis of a particular exam type, then the experimenter must make sure that the image on the CRT display matches the original in

every way except for the spatial resolution. If the other characteristics of the CRT are not controlled for, then the results of that study do not reflect only spatial resolution differences, but also all the other uncontrolled variables in the system. Thus, no specific conclusions about spatial resolution can be made. This paper (1) describes some of the techniques that we have developed to control CRT displays and laser writers and (2) presents results from studies that show the deleterious effects on perception when display characteristics are not controlled.

DISPLAY TYPES

CRT Displays

When a digital image is displayed on a CRT there is usually not a one to one mapping of the digital values in memory to that which is seen by the observer at the surface of the screen. The CRT and the driver board combine to distort the values actually written to the screen. These two devices and the other electronics in the system contribute to the system greylevel/brightness transfer curve. Depending on the amount of change brought about by this transfer curve this distortion can have drastic effects on detection. A way to account for this is to characterize the transfer curve of the CRT system to be used in the research and then control its output using that information.

We have developed a simple procedure for characterizing the greylevel/brightness transfer curve of a CRT system. First an SMPTE test pattern is written to the screen and the contrast brightness controls are manipulated until the 5% and the 95% difference squares are clearly visible. The brightness and contrast controls are then locked in place and a series of greylevels are written to the CRT screen and the light output is then measured in foot lamberts for each of the steps displayed. We use a simple silicon detector attached to a voltmeter with a digital display to take these measures. We attach the detector to the center of the screen, cover the screen to eliminate scatter due to ambient light and then take the measurements. We have used more elaborate controls and equipment to take these measures [5,6,7], but for characterizing the transfer curve of a CRT display system, we have found this simple technique worked as well as the other.

Figures 1 and 2 are the transfer curves of two different display systems. The same CRT was used in both cases. The only difference was the driver board we used. One was hooked to our VAX 8600 system. The other was in a PC based system. While both have non linear shapes, they are different. Putting the same information into the two systems results in different brightness outputs. We found that these differences have a significant effect on an observers detection capabilities. Figure 3 describes the results of a study we ran to investigate the effect of transfer curves on detection. We displayed the same set of images on the two different display systems characterized in Figures 1 and 2. The images had a noisy background and the signal, when it was present, was always in the center. There were five levels of signal. The images were shown to 6 observers one at time, in random order, and in a controlled experimental environment. The ROC experimental paradigm was used and the observer's task was to

tell us their certainty that a signal was present or not. The two curves in Figure 3 are the results of this study. As expected, in both cases as signal increases so does detection. However, the detection of the PC based CRT system is lower than that on the VAX. Efficiencies were calculated $[(dH/dI)**2]$ comparing the human (dH) to an ideal observer (dI) and as can be seen the PC based system is 35% $[(10-6.5)/10*100]$ lower than that of the VAX.

Once you have determined the shape of the transfer curve it is a simple matter to make a look-up-table (LUT) to change the curve to any desired form. We photometrically linearized our displays and then ran a second study using the PC system to investigate the effect of linearization on detection. The same images and the same observers used in the previous study were used. The task and the experimental environment were the same. With photometric linearization there was a further decrease of 76.9% $[(6.5-1.5)/6.5*100]$ in efficiency from the results of the previous PC study. This decrease in detection capabilities can be explained by the following: when these monitors were linearized, there was a reduction in slope of the transfer curve in the greylevel region in which the signal to be detected, resided. Thus, signal decreased for the observers.

It should be noted that although the transfer curves depicted in Figures 1 and 2 are commonly encountered in a large range of CRT displays, other transfer curves are possible and they might lead to different effects. For example, if linearization has the effect of increasing the slope of the transfer curve in the range of greylevels in which the signal resided, then detection would most likely be increased. However for the range of displays that our transfer curves represent, photometric linearization is obviously not a good candidate for a general display transfer curve.

These studies show how easy it is to affect the perception of observers and to distort their type of conclusions that are drawn from research using CRT displays. Next, we will discuss controlling laser written film to equate optical densities in the duplicate film to the original.

Laser Written Film Displayed on Light Boxes

An alternate way of displaying digitized images is to write them back to film and then display them using a light box. For example, suppose you wanted to investigate the effect of reduced spatial resolution on diagnosis. Affordable and available CRTs cannot display image matrix sizes much over 2000 X 2000 pixels with, at least, 8 bits of grey. This means that images having larger matrix sizes would have to either be displayed piecemeal or displayed by using a reduced matrix size. Neither method is very acceptable for this type of research, thus writing back to film is a popular method for investigations into spatial resolution needs. After the images have been digitized and the appropriate manipulations made to reduce resolution, but before writing them back to film, a crucial step must be taken. A LUT must be devised that will maintain the same optical densities in the duplicate images as those found in the original films. If this step is not taken before generating the images, then the results of such a study will be confounded due to this lack of experimental control.

To avoid this problem we have developed a procedure to insure

that the optical densities of duplicate images will be virtually identical to those of the original. When we digitize the films to be used in our studies, we also digitize the National Bureau of Standards (NBS) x-ray step tablet. This tablet has 17 steps of optical density ranging from 0.20 to 4.15. For this work we only use the first 14. The 14th step has an optical density of 2.89. Next we use a computer program to find the average greylevel for each step in the digitized NBS tablet. We then calibrate our Kodak laser writer and film processor to stabilize the output and write out the digitized NBS step tablet. We also write out a digital step tablet that we create in the computer with a greylevel range dependent on the number of bits there are per pixel. For example, if the number of bits is 12, then we create one that ranges from 0 to 4095 in steps of 32. We then process the two images and measure their optical densities. Having the digital and optical density values for both step tablets allows us to make a LUT that, when down loaded into the Kodak laser writer, adjusts the laser's output to equate the optical densities of the laser written NBS step tablet to those of the original.

We did the above process for a set of images we are using in a spatial resolution study. Figure 4 shows the closest we can come to the original NBS step tablet using just the controls built into the Kodak writer. There is some correspondence up to around 2.20 optical densities, but after that point the two diverge significantly. Figure 5 shows measurements of the laser written NBS step tablet with the same control settings as the previous one, but now with our LUT also incorporated into the system. There is virtually identical correspondence for all 14 steps. The last one is only off by 0.01 optical densities. Using the LUT we then wrote the images to be used in the resolution study. Figure 6 shows how closely the images we wrote using the LUT match the original. Sixteen locations were measured for one original image and the same 16 locations were also measured in two duplicate images. One duplicate was written with and one was written without the LUT. As can be seen, the two curves are very similar to those we found using the NBS step tablet. Thus, we feel that we have produced images that vary only in terms of their spatial resolution and the results from our study will reflect only the manipulation of that parameter. As figure 6 demonstrates, without the LUT this would not have been true.

DISCUSSION

In the PAC/IMAC field researchers are asking subtler and subtler questions about system needs. Thus, the need for controlling all aspects of the experimental environment becomes even more important than in the past. We hope to have demonstrated in this paper, (1) that small differences in display characteristics can have large effects on perception, (2) that control of all aspects of the display system is necessary for valid results, and (3) that this control is also possible. Without characterization and control of the kind described in this paper, experimental results and conclusions will have very limited generalizability and usefulness.

Acknowledgements: This work was supported by NIH Grant Numbers P01, CA23417 and R01 CA49261.

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FIGURES

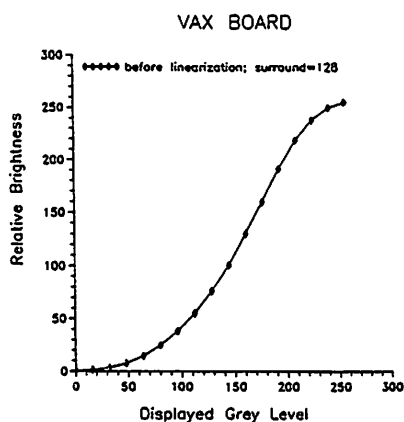


Figure 1. Transfer curve for display board in VAX 6600

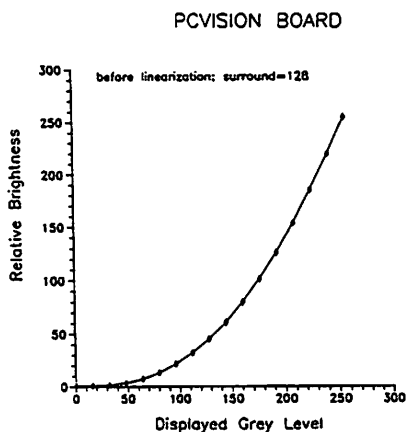


Figure 2. Transfer curve for display board in PC.

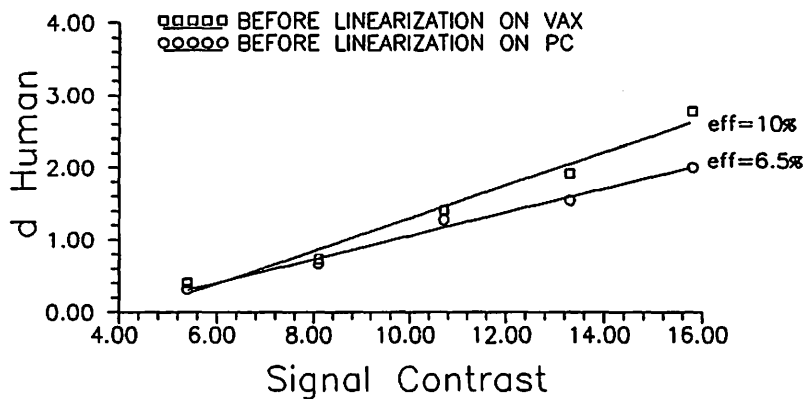


Figure 3. Results from transfer curve psychophysical experiments

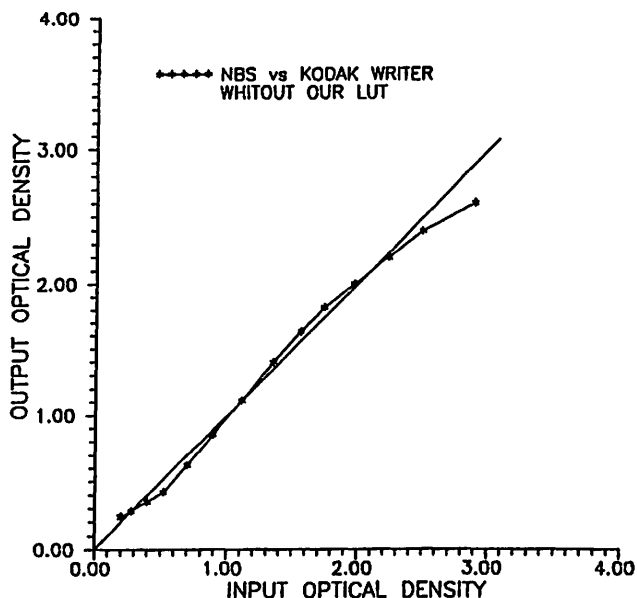


Figure 4. Laser writer output of digitized NBS tablet without LUT

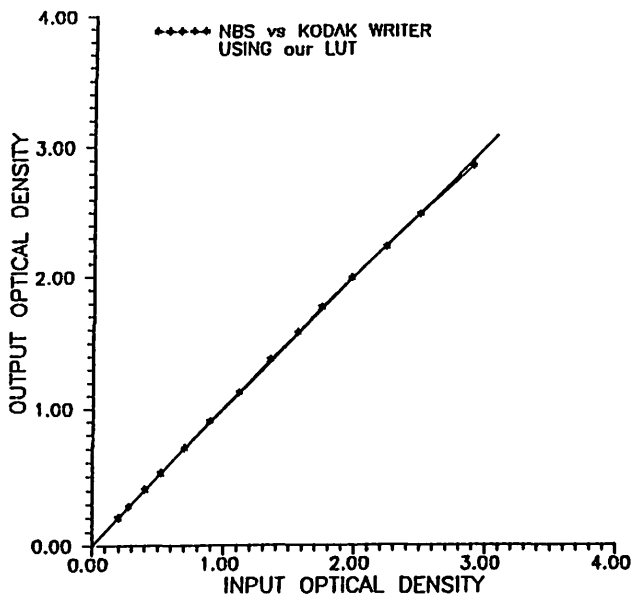


Figure 5. Laser writer output of digitized NBS tablet with LUT

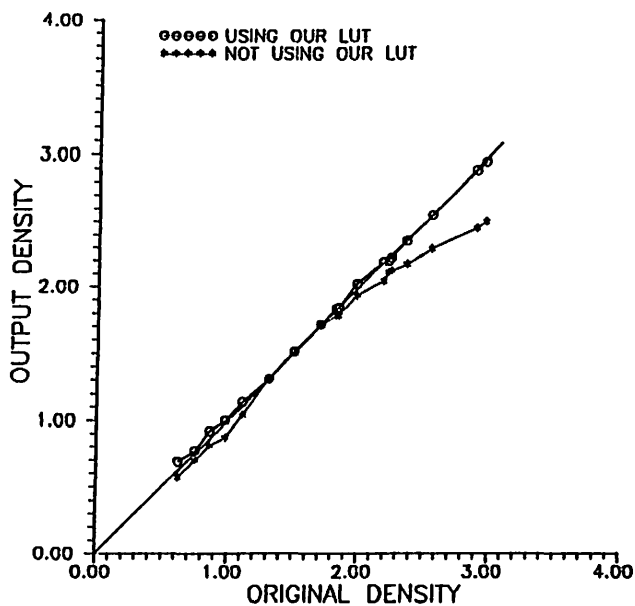


Figure 6. Sixteen measurements taken from an original image and compared to those taken from laser film images written with and without the LUT.

A Manufacturer's Perspective on Desktop Workstation

Charles L. Hall

Siemens Gammasonics, Inc., Hoffman Estates, IL

ABSTRACT

Siemens has developed and introduced a desktop workstation - the "LiteBox" - based on the Apple® Macintosh® computer. The focus of the development has been to build a powerful, easy-to-use, low cost imaging workstation. The LiteBox's applications in medical imaging range from Radiation Therapy to Magnetic Resonance Imaging; and from Intensive Care Unit to referring physician's office.

The development has raised several questions that a medical imaging equipment manufacturer has to consider and decide when introducing a personal computer-based product that impact the radiology end user and other medical staff. Some of these questions are:

1. Is the "LiteBox" a system (hardware and software) offering or a software only product?
2. What are the Medical Devices regulatory issues for a software only product?
3. What are the service and maintenance considerations?

This presentation will review the impact of these issues on the end user and the manufacturer. Other areas that will be reviewed are price/performance and medical-legal issues.

X Image Extensions to the X Window System Implications for Medical Imaging Applications

Edward J. Rudack

Digital Equipment Corporation, Marlboro, MA

INTRODUCTION

This paper reports on the X Window System as an industry standard building block for creating the graphical user interface on bitmapped workstations and promoting open systems. It also reports on the proposed image extensions to the X Window System which enhance the architecture for building image capable information systems. The continuing decrease in the price/performance ratio in compute power, data storage and network bandwidth makes it technologically and financially feasible to incorporate image capabilities in all types of medical applications[1]. While the advances in medical imaging technologies have given physicians better diagnostic tools, the wide spread use of images in the healthcare environment will result in better patient care efficiency and increased physician productivity. A solid information system foundation is a critical predecessor to any image system.

The X Window System provides an important standard and imparts a new approach to problem solving by allowing access to information resources throughout the hospital. This software architecture provides the ability to transparently access information and applications from anywhere on the network, across multiple operating systems and hardware platforms. As the use of images becomes more commonplace in all applications the need and use of standards will continue to provide benefits by decreasing the cost and time

to develop applications. The use of these standards also insulates the applications from the underlying technology, protecting investments in software design and development.

HISTORY OF THE X WINDOW SYSTEM

The X Window System was originally developed under Project Athena at the Massachusetts Institute of Technology (MIT), jointly with Digital Equipment Corporation and with contributions from several other companies[2]. Widespread use of the X Window System in the Unix community was established with the release of Version 10. The X Window System continued to grow in popularity and to evolve with major enhancements in Version 11 and the current MIT release is X11R4.

In January of 1988, the MIT X Consortium was established to continue the development of the X Window System and currently has over 70 members and affiliate institutions. It has as its major goal the promotion of cooperation within the computer industry for the creation of standard software interfaces at all layers in the X Window System environment.

Two other significant activities which contribute to the wide spread use of the X Window System are also in process. They are the OSF and ANSI standard proposals related to the X Window System.

The Open Software Foundation (OSF) has specified OSF/Motif as the application programming interface of an X Window System based environment.

The ANSI standard proposal for the X Window System is in draft in the X3H3.6 Window Management Task Group.

DESIGN GOALS OF THE X WINDOW SYSTEM

One of the original goals of the X Window System (or simply X) was to establish a portable device independent window

system for bit mapped displays. Device independence is achieved by separating the X Window System into two parts using the client/server model. The X server controls the hardware specific devices and implements instructions from the client.

Not only was X designed to be hardware independent, it was also designed to be network transparent and network protocol independent. X clients communicate with X servers by sending packets of instructions using the X protocol. The X protocol is the metalanguage that describes how things will be done on the display and the interaction with the devices the X server controls. As long as the server has reliable communication to the client application, they may physically be across the network or reside on the same machine. By concise definitions of the semantics of the X protocol, it is made independent of the operating system, network transport technology, and the programming languages[3].

The X Window System provides the mechanism for drawing windows, but not the policy for user interface or using windows within applications. The window manager is responsible for imposing a policy and the look and feel of the user interface.

Finally, the X Window System was designed to be extensible. This would allow certain classes of users to add features within the X framework[4].

X WINDOW SYSTEM ARCHITECTURE MODEL

The core X Window System consists of 3 major components, the X server, Xlib and the Xtoolkit, as shown in figure 1. The X protocol separates the hardware dependent X server by means of Xlib and the Xtoolkit from the application. This arrangement means that applications can reside on different computers in a network and direct the output to any X server on which it has permission. Using the X protocol as the

window system metalanguage also means that applications do not have to be recompiled or relinked to execute on a new workstation/display. It is only the X server that is hardware dependent.

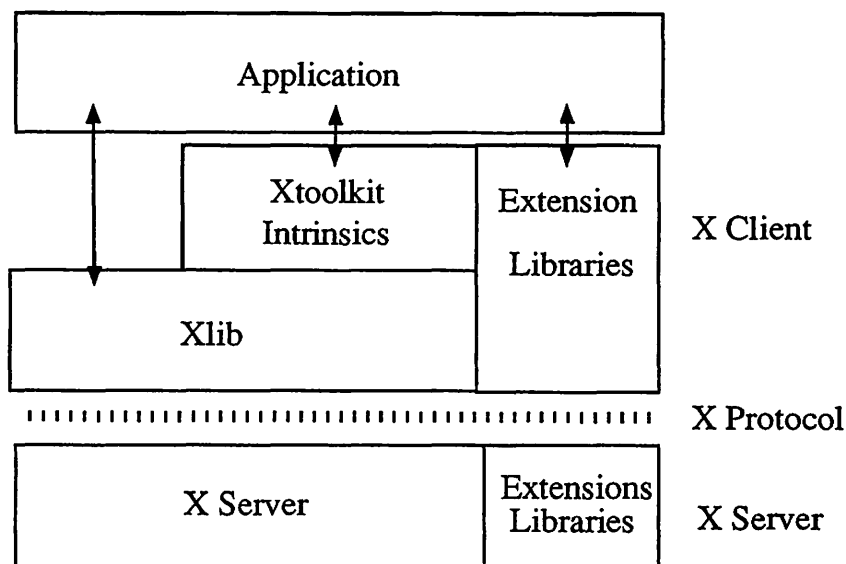


Figure 1. X Window System Client/Server Model

X server is the code which runs on a workstation or X terminal. It provides a low level graphic interface to the display and user input capabilities, such as mouse and keyboard.

Xlib is a library of X protocol access routines provided for the application programmer. By using Xlib routines the programmer has access to all X resources and results in highly transportable code from one operating system to another operating system. Xlib generates the appropriate X protocol messages for transmission to the X Server. The transmission may be by the network (DECnet or TCP/IP) or in the case when the X server and client are on the same workstation by shared memory or other interprocess communication.

The Xtoolkit provides additional routines to simplify the application access to Xlib. The two logical components of the Xtoolkit are called X intrinsics and X widgets. X intrinsics are well defined in the X Window Systems and are used to write higher level tools called widgets. Examples of widgets are pull-down menus, scroll bars, toggle buttons which implement features on the user interface.

RELATIONSHIP OF DECWINDOWS TO X

DECwindows is based on the X Window System and is fully compatible with X, but extends the architecture in a number of significant ways[7].

- o Quality of implementation of the X components
- o Choice of programming languages interfaces
- o DECwindows Toolkit Widgets
- o Industry standard Xtoolkit interfaces
- o Extension libraries
- o Window and Session Managers
- o Terminal emulators
- o Personal productivity tools

A comprehensive model of the DECwindows system is shown in figure 2. The client application can interface to Xlib, Xtoolkit intrinsics, Xtoolkit widgets, industry standard graphic libraries such as GKS, or to the X extension libraries.

On the client side, the staircase layering of the application demonstrates the ability for applications to intermix calls to any of the client-side libraries. This important feature allows applications to take advantage of DECwindows toolkit if a high level of abstraction is desired, or the Xtoolkit if portability is desired.

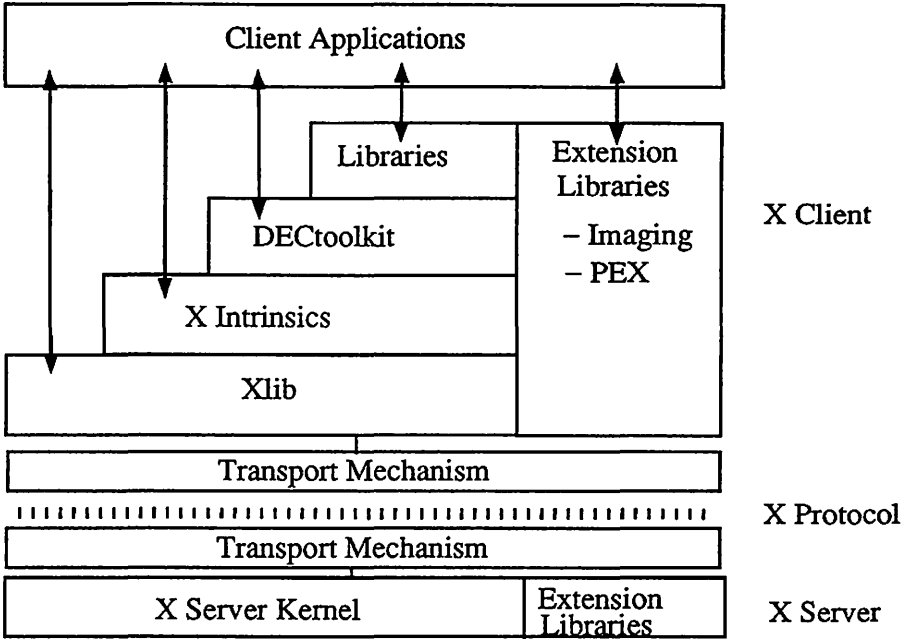


Figure 2 DECwindows Architecture Model

X EXTENSIONS FOR IMAGING

As with industry standard libraries, extensions can be made in the form of custom widgets. DECimage Application Services provides a set of custom widgets in the X environment which simplify the programming when images are manipulated[6]. Custom widgets typically are implemented using Xlib and X intrinsic calls[5].

The X architecture supports an extension facility so that functions can be added to the core routines. An extension consists of two parts, a hardware dependent extension to the X server and a client side library. Thus, X does not restrict hardware innovation for imaging or 3D graphic applications.

Extension functions for image may include data compression/decompression, image scaling and rotation, image enhancement and color transformation.

The core X protocol provides a means for a client application to transmit and display images, however, it requires that most image manipulation take place on the client side of the application. Thus, applications can not take advantage of hardware acceleration which may be present in the display.

X image extensions propose the following;

- o Image data extensions
 - including compressed images
- o Image manipulation and enhancement

These move the device dependent processing functions from the client application into the server and allow the server to take advantage of hardware acceleration while still retaining device independence in the application.

CONCLUSIONS

The wide spread use of image applications in the healthcare environment will require the interoperability of a number of different computer systems and display devices.

The X Window System in its current form provides software architecture which allows image applications to display images across a number of different computers, displays, and operating systems.

The proposed X Image Extensions allow this same software architecture to take advantage of the hardware acceleration in these display devices and maintain portable image applications.

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Q-RSTAR Workstations and System: Technical Overview

J.L. Taaffe, M. Kaldis, J. Gahm, et al

Department of Radiology, Massachusetts General Hospital,
Boston, MA

Introduction

Since late 1984 the Massachusetts General Hospital (MGH) Department of Radiology has been actively developing PACS technology. This paper will discuss the overall system architecture of our most current development project, the Q-RSTAR (Radiology Storage Transfer Analysis and Reporting) system which has been under development for the last 18 months. We are currently installing portions of this technology in the department and intend to further deploy this technology throughout the hospital during 1990.

The Q-RSTAR system is a direct outgrowth of our experience with its predecessor, the μ RSTAR system, that has been used clinically for over two years at the MGH. The μ RSTAR system was intended to be a research system operating primarily to increase our understanding of the requirements for a full PACS. Q-RSTAR has been designed with the knowledge and experience gained from the μ RSTAR development and its clinical use. The main focus of Q-RSTAR is that of providing clinical utility to the department, the hospital, and affiliated institutions. Of the 16 Q-RSTAR workstations being installed in 1990 and early 1991, all but 3 are for direct clinical use.

Basic Q-RSTAR Functional Specifications

The next few paragraphs will provide a cursory description of the basic functional specifications of Q-RSTAR at this stage of its development.

There are two classes of Q-RSTAR workstations: medium resolution, those based upon 1.2K x 1K color or monochrome displays; and high resolution, those based upon 2K x 2.5K high frame rate monochrome displays. The workstations, based upon Apple Computer Macintosh, are designed to be multimodality, capable of manipulating CT, MRI, and various nuclear medicine images, as well as high resolution digitized radiographs. Animation and/or cine loops of selected image sets are provided for. The workstations will be 'multimedia' in the sense that they will provide for the spatial and temporal orchestration of image and graphics data as well as voice data. Image manipulations such as smooth zoom, flip, rotate, and window and center are provided for through the use of a local vector processor/pixel-mover. From our experience with μ RSTAR we have become

convinced of the need to have a capable, forgiving, yet simple user interface. In our effort towards reaching this goal we intend to deploy an interface guided by a number of expert systems to aid the user in 1991.

The Q-RSTAR communication system is structured around a 'dual LAN' (local area network) concept: Ethernet for command & control information and a variety of high-bandwidth 'image blasters' for image transport within the MGH main campus and the MRI facility in Charlestown. This dual LAN concept yields an affordable communications system with an application performance for image transfer of over 10 megabyte/sec.

Between the locations listed below we have in place standard telephone DS3 circuits operating at 45 megabits/second as well as 1.5 megabits/second T1 lines carrying Ethernet to interconnect Q-RSTAR subsystems. These lines allow data interchange between all locations and provide application data transfer rates of over 4 megabytes/second. The current locations are:

- The MGH main campus in Boston
- The PACS Development Center in Cambridge
- The MRI Center in Charlestown
- The Film Library in Somerville
- The Spaulding Rehabilitation Hospital in Boston
- An HMO in suburban Boston

The image archive currently consists of two 1-Gigabyte (GB) optical drives with removable media (Digital Equipment Corp. RV20 drives), 6.8 GB magnetic disk arrays used as image caches (MGH designed), and 1.5 GB of magnetic disks used as image working disks. We are currently evaluating various juke-boxes to be integrated into the system. The μ RSTAR system supported an extensively catalogued off-line magnetic tape archive, and we are presently porting this software with enhancements to the newer Q-RSTAR system to support off-line optical media as well. The logical structure of the demographic database allows for the reception and generation of ACR/NEMA compatible data elements.

Shared among the workstations is a multiplexed, 40 MIPS image processor capable of over 80 megaflops constructed from multiple Mercury Computer Systems Inc. array processors, model number MC-32-NU-8.

The overall system is controlled by a Digital Equipment VAX 6220 currently with 64 megabytes of main memory used solely for the RSTAR project.

Design Goals and Considerations

In discussing the goals for the Q-RSTAR system, it is useful to view the goals from three perspectives: that of the user, of the department, and of the system designer.

For the Q-RSTAR system to compete successfully with the existing film-based system with its over 60 film librarians, the Q-RSTAR workstation must: 1) present diagnostic quality images, 2) display these images in a fraction of a second on request, 3) be easy to use, and 4) be able to display any image known to the system at any workstation with equal ease and speed.

From the department's perspective, if Q-RSTAR is to be viable it must be deployed throughout the department and the hospital. Thus the workstations must be affordable since there will be many of them. Therefore, the workstations must be built upon inexpensive platforms that also offer the necessary performance. Additionally, the overall system must be highly reliable.

The designers of Q-RSTAR have taken the position that there will be no local storage at the workstations. Specifically, we wish to remove any geographical dependence at the workstation --- any workstation has equal access to all images, via the high speed LAN, and to a large and high performance image cache. The Q-RSTAR system from its inception has been designed to be distributed, redundant, expandable, and modular.

Major Design Concepts

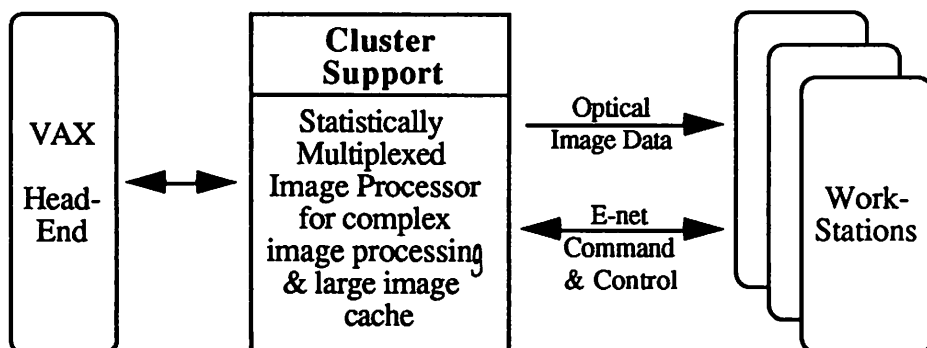


Figure 1 : Shared Image Processor

To meet the requirement of no local image storage at the workstation (that is, no large image storage disk; however, there will be an image cache consisting of high speed memory), we have designed what we call a Cluster-Support unit, (see Figure 1). Each Cluster-Support unit contains a 3.4 GB magnetic disk array capable of transferring images at the approximate rate of 8 megabytes/second. By using the

information about active patients obtained from our radiology exam scheduling system (Digital Equipment Corp's. DecRad), we are able to place the necessary comparison and teaching files within the disk-image-cache as well as the images associated with the unread exams. Thus, upon a request from a workstation for a particular image, one that is likely to be found within the disk-image-cache, the Cluster-Support unit will be able to transfer the image data quickly to the optical image LAN.

As shown in Figure 1, we use conventional Ethernet to transfer command & control information between workstations and the Cluster-Support unit. Since Ethernet is inadequate to send high resolution images in a timely fashion, we use an MGH designed 100 megabits/second optical LAN based upon Advanced Micro Devices Inc. TAXI components.

Every user must have the ability to perform complex image processing in a timely fashion. A simple method of providing this functionality is to place at each workstation a high performance image and/or vector processor. The problem with this approach is that the workstation cost escalates with the inclusion of a device that will likely be used a very small percentage of the time. Instead, we have taken the approach of placing at the workstation minimal image processing hardware, sufficient for operations such as smooth zoom, flips, rotates, etc., and placing in the Cluster-Support module a high performance image processor that is shared or multiplexed between all the workstations (with its attending cost essentially amortized among all the workstations). For example, if a workstation wishes to perform a complex image processing task (e.g., an oblique reconstruction) the workstation will make a request via the command & control channel to the Cluster-Support unit. It will transfer the images from the disk-image-cache to the shared image processor that will then perform the necessary calculations. Finally, the new images will be transferred via the high-speed optical LAN to the requesting workstation. Note that by using this architecture it is unnecessary to ever have to transfer image data back from the workstations to the Cluster-Support unit. Thus, the optical image LAN need only be capable of transmitting images in one direction --- from the Cluster-Support unit to the various requesting workstations.

The Q-RSTAR System

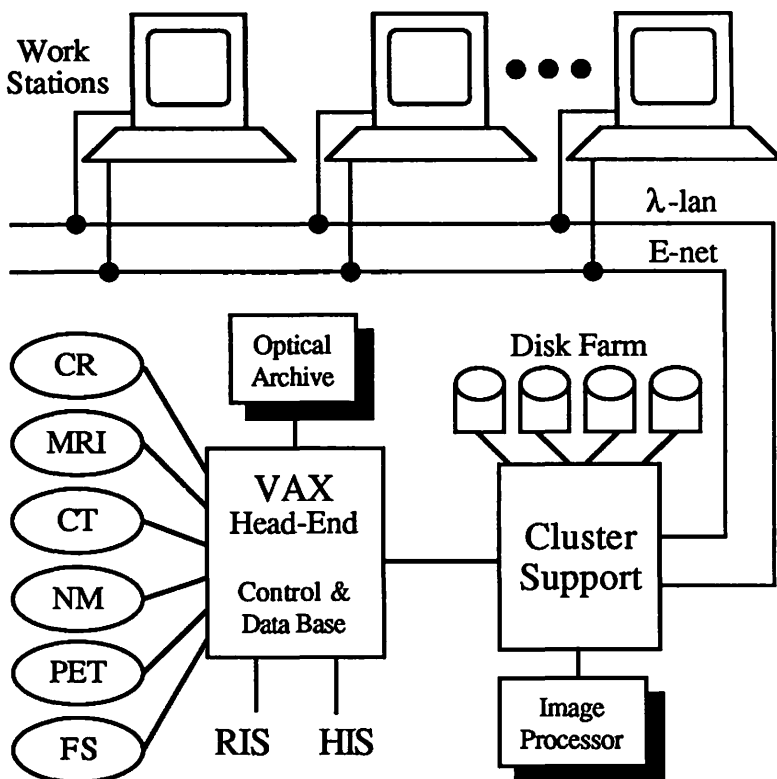


Figure 2 : System Architecture

As shown in Figure 2 above, we use a VAX computer for overall system control, as well as exam collection and formatting, managing the patient demographic database, managing the image archives, hosting various expert systems, and interfacing to the hospital information systems (HIS) and the radiology information system (RIS). The VAX Head-End is connected to one or more Cluster-Support units that in turn provide services for approximately 20 workstations. Note, in the current configuration of Q-RSTAR, we are using the dual LAN concept as explained above; however, we plan to migrate to the FDDI (fiber distributed data interface) LAN standard as the cost of this technology decreases.

Figure 3 outlines a Cluster-Support unit. We base this subsystem on the Apple Computer Corp's. Macintosh computer for price and performance considerations. In particular, the NuBus standard supports sustained data transfers across the bus of 37.5 megabytes/second; we are thus able to transfer image data either from the image-disk-cache or image-cache-memory at high rates. The Cluster-Support unit

receives image data from its VAX master by a high speed parallel interface, a Digital Equipment DRB-32 on the VAX side. In some versions of the Q-RSTAR system the parallel interface's functionality is replaced by the existing Ethernet interface.

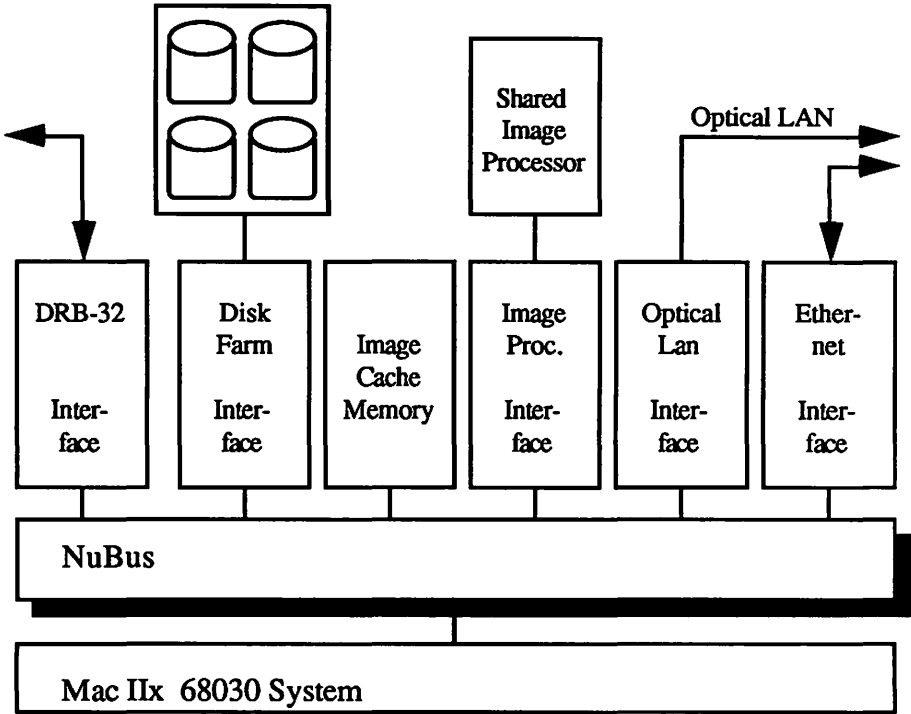


Figure 3 : Cluster Support

Figure 4, shows a representative Q-RSTAR workstation. The Ethernet interface is used to convey command & control information between the workstation and the Head-End VAX and the Cluster-Support unit. High speed image data transfers from the Cluster-Support unit are received by the optical LAN interface and placed into the image cache & buffer. This buffer of between 4 and 16 megabytes holds the most recently used images and is used as a statistical cache. If the user performs repeated operations upon a small set of images, the needed image data is likely to be found in this cache negating the need to request service from the Cluster-Support unit. As mentioned earlier, each workstation contains a simple pixel-mover capable of very simple image processing operations. The primary function of the pixel-mover is to copy image data from the cache buffer to the display controller while at the same time performing the needed image transform such as flip, rotate, zoom, etc. The workstations support all Macintosh compatible display controllers, in particular the MGH designed 2K x 2.5K unit. Our experience to date indicates that the choice of Macintosh as the workstation

platform has been a good one. The wealth of software available, in particular user interface tools, has greatly enhanced our efforts.

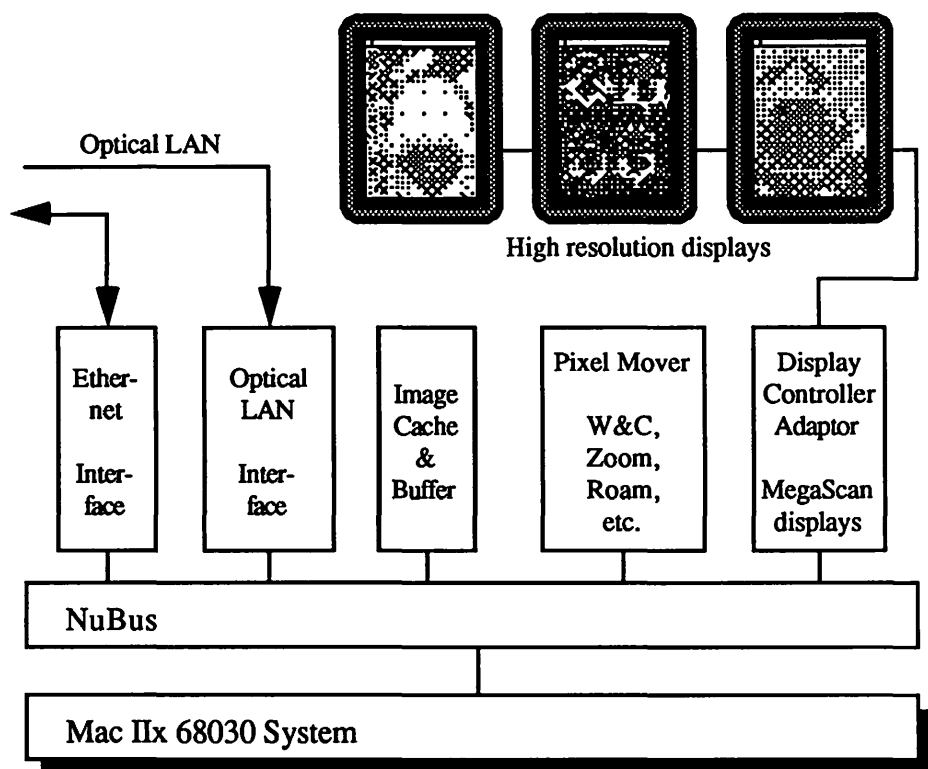


Figure 4 : Workstation Hardware

Status of the Implementation

At this time we have major portions of the system implementation and are currently deploying the technology in selected areas of the department. By year's end we expect to have the high-resolution workstations throughout the department as well as in selected areas outside of the main campus. In particular, we already have a high resolution digitizer (DuPont Corp. FD-2000) located at our Somerville film library that sends images to the main campus as needed. It is proving to be a most gratifying and exciting time for the MGH PACS development group and the department.

Critical Characteristics of Radiology Workstation Navigation

David Beard

Departments of Radiology and Computer Science,
University of North Carolina at Chapel Hill, NC

PACS technology is at the point that a number of institutions are considering the purchase of radiology workstations. Yet no available design is appropriate for all clinical situations. This paper discusses the pros and cons of various computer human interaction or "navigation" design alternatives for a primary interpretation workstation. Other important non-navigation issues such as image quality, cost, and system integration are ignored. First, we detail a requirements taxonomy, focusing on both the minimal features required for a typical clinical interpretation as well as more advanced characteristics. Second, we consider ease-of-learning with a discussion of the importance of mental models or metaphors. Third, we detail a number of critical issues effecting ease-of-use. Simple design evaluation tests are provided to help the reader understand the design issues as well as select the appropriate tool.

REQUIREMENTS ANALYSIS

Tools are only "good" or "bad" relative to a user and a task. Thus to evaluate a radiology workstation, we must determine *who* will use it to do *what*. This seems simple, but often tools are required to serve multiple users, each performing a variety of tasks. We assume that the primary purpose of the workstation is viewing, by the radiologist, of images in the patient folder for the primary diagnosis. Thus the workstation must first serve as a viable alternative to the four-over-four viewbox. Then (and only then) we can consider any "bells and whistles," which is to say more advanced features. It is all too easy to design a workstation focused on the bells and whistles, which ignores many of the more mundane, though essential features.

Critical Function

On our opinion, the following function is essential for a primary diagnosis radiology workstation. First, users must be able to locate specific patient folders. This requires integration with the Radiology Information System (RIS). Second, they must be able to rapidly locate specific studies or images within the patient folder. Third, radiologists must be able to display any image at full resolution. Fourth, they must be able to move sequentially through a multiple-slice study

and roam around within a plain film larger than the display screen(s). Fifth, they must be able to side-by-side compare images from different studies, such as left and right mammograms, or this weeks and last week's CT chest study. Sixth, radiologists must be able to adjust the displayed image's intensity-window width and level, both by modifiable presets that vary with image type, and dynamically. While contrast-adjusting entire studies may be sufficient and is simpler, many radiologists may want to adjust individual images.

"Bells and Whistles"

The following features would be desirable for a workstation that successfully implements all the basics. First, tools for measuring distances across images. Such a tool would allow the radiologist to measure the length of a tumor or other anatomical object. Second, an electronic grease pen for highlighting critical anatomy for future readers. Third, zooming, either continues or bilinear. There may be situations in which zooming should be considered essential, but a simpler full resolution display with a pictorial index seems to provide sufficient spatial context for many modalities [Beard 1988] without the added hardware or computer-human-interaction complexity of the zoom operation.

Fourth, 3D display of multiple-slice studies. Currently however, given the poorer quality of the images, 3D probably is of more use to surgeons trying to understand the spatial interrelationships of their patient's anatomy, than to the radiologist generating an interpretation report. Fifth, contrast enhancement algorithms, which may be useful in many situations for improving feature detection.

Functional Evaluation

While one can simply read the marketing and technical documentation provided by the workstation vendor to determine function, it is best to sit down in front of the tool and actually try to use each one. It is important to realize that just because a workstation has a particular feature, does not mean that an average radiologist can actually use it. Thus the actual feature list of a workstation, as opposed to the advertised one, is highly dependent on the workstation's ease of learning and ease of use as detailed below.

EASE-OF-LEARNING

Automated office tools, like radiology workstations, can be threatening to a skilled professional: they eliminate the need for skills carefully developed over many years; they often force the user to submit to instruction by younger, less experienced individuals; and they can make the user feel like a child. These are problems with any new tool, but the harder a tool is to learn, the greater the affect. Thus ease-of-learning is critical to user acceptance of radiology workstations.

To learn how to use a tool requires constructing a *mental model* [Rumelhart 1981, Young 1981] of its operation. Mental models can be hard to acquire, so computer tools are often build to be analogous to some metaphor of physical reality such as a desk top [Macintosh 1988]. Mental models are used in radiology workstations to facilitate two tasks: locating studies within patient folders and determining their temporal and spatial/anatomical relationship, and as an *image index* for locating images within studies and determining their temporal and anatomical position. We consider the pros and cons of several mental models currently used in radiology workstations.

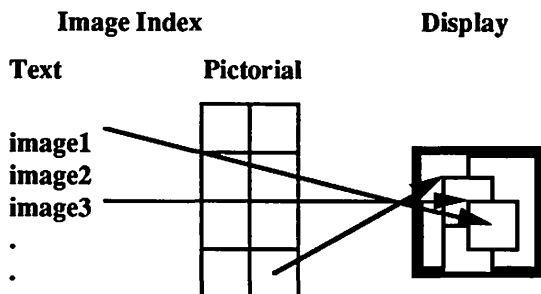


Figure 1
Desktop Metaphor with Manual Positioning
of Individual Images

Figure 1 shows a desktop metaphor used with some radiology workstations. With this mental model, individual images are selected from an *image index*, either a text index or a pictorial index consisting of miniatures of all images [Beard 1988], and the individual images are separately moved to various positions on the display. This approach is simple to understand and works with both single and multiple studies [McNeill 1987]. It is quite appropriate for viewing patient folders containing a small number of large radiographs. However, the metaphor begins to breakdown when used with multiple-slice studies because of the considerable number of hand-motions required and the fact that the display can become messy and confusing. While some workstations allow entire studies to be moved to multiple displays in one step, they still suffer from the problem of excess handmotions, because too many images must be individually moved for essential side-by-side comparison.

Figure 2 shows another common metaphor in which each display has an image memory sufficient to contain part or all of an either study. The top three displays use the FilmStrip [Beard 1987] metaphor. It is most appropriate when viewing

multiple-slice studies. The bottom three use the metaphor of a viewport into an image display space. It is most appropriate when viewing large radiographs.

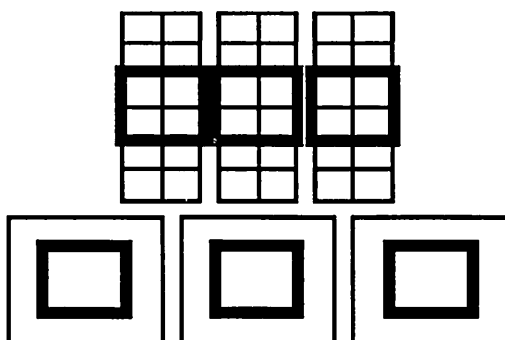


Figure 2
Individual Image Memories for Each Display

However, only a limited amount of image memory is available to each screen, and often, there is not enough to display an entire study. Then the radiologist is forced to spend valuable time managing the memory resources of the computer. Further, since parts of a study may be spread among several displays, it becomes difficult for the radiologist to remember which slices of which study are located in which display. A great deal of time and effort may be spent simply moving studies to the various displays and keeping track of their locations.

The metaphors in figures 1 and 2 are appealing to system builders because of the parallels to the memory organization of the typical workstation. Because the user, not the tool, moves studies from disk and workstation memory to the various display memories, the developer can conceal slower data-path speeds and avoid developing complex memory management software. While this metaphor may reduce workstation cost, it is less than optimal for radiologists.

We prefer to use the FilmPlane mental model (Figure 3), in which the images remain stationary relative to one another in the metaphor and the display or displays are moved to the appropriate images. FilmPlane uses a metaphor of the lightbox, in which radiologists most often moves their eyes to the image, rather than the image to their eyes. The *Viewports* on the *Navigation View* in the center display can be manipulated with the mouse allowing any random image to be displayed on any display. Further, the individual *Detail views* on the left and right displays can be scrolled up, down, left, or right. A subject experiment conducted with a similar interface to a Hypertext system indicated that navigation views significantly improved information access [Beard 1990a].

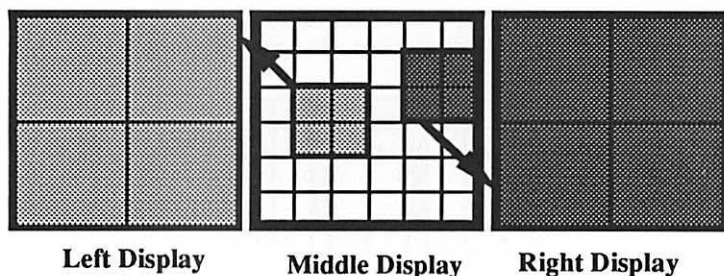


Figure 3
FilmPlane Metaphor

FilmPlane, as with most of the currently available radiology workstations, uses the direct manipulation interface style. Direct manipulation interfaces allow the user to "physically" manipulate metaphor objects on the screen, extending the mental model from comprehension to interaction. For an application involving visual objects such as medical images, the direct manipulation approach is almost essential. However, designing a viable direct manipulation interface is difficult, and there are many examples of systems that have a mouse, pull down menus and an impressive look, but are far too difficult to use.

Ease-of-Learning Evaluation

Users have learned the basics of a radiology workstation when they can locate and display a randomly selected image in the patient folder, sequentially move through a multiple slice study, side-by-side compare images from different studies, and adjust image contrast both dynamically and with presets. We feel that with a well-designed workstation, a typical user should be able to confidently do these tasks after less than 15 minutes training. Ease-of-learning is best evaluated by bringing the tool in-house for a month or so and having the entire staff participate. But quick evaluations are possible at trade shows as long as the users conduct the trial tasks with only little coaching by the observer or salesperson.

EASE-OF-USE

While ease of learning effects users' understanding of the system, ease-of-use effects user's performance and frustration level. The following are several critical areas of ease-of-use.

Response time: Response time requirements vary with the number of images being viewed and the average per-image viewing time. We suspect that response times for multiple-slice studies should be under one second for scrolling a screen with under a half second being desirable (this depends on the size of the screen).

The larger the image, the longer it takes to read it, so a longer response time for larger images should have less impact on total interpretation time.

Errors: The interaction should be designed so that even beginning typical users make few errors e.g. selecting the wrong image, command, or mode. Most importantly, users should never have difficulty locating a study or image, or determining from which study an image was taken. If one or more users continually repeat the same error, the fault lies with the workstation design, not with the users.

Hand Motions: There should be an absolute minimum of hand motions required for conducting a diagnosis, and one should almost never have to move individual images. For example, FilmPlane2 requires only one keystroke per movement to side-by-side scroll through two CT chest studies. Many workstations require over 10 keystrokes per movement to perform this same task.

Display Area: Our work with an eyetracker [Beard 1989] indicates that there should be sufficient monitor space to show at least 12 CT images for CT interpretation. We estimate that even more would be desirable for radiographs [Pizer 1989]. Primary interpretation workstations may require as many as four 2kx2k monitors.

Intensity Windowing: The radiologist must be able to adjust the displayed intensity values of the images. A number of different approaches to dynamic intensity windowing have been tried including using mice or trackballs with horizontal motion controlling window width and vertical motion controlling level (or vice versa) as well as sliders and various buttons. Many radiologists have different interaction preferences depending on their experience and task, and dynamic windowing control is often discussed in the literature, but we are aware of no definitive study on this subject. Dynamic intensity windowing requires a significant amount of time, so many radiology workstations offer *preset* buttons that automatically adjust an individual image or study to a some window width and level that is felt to best display particular anatomy. These preset values should vary with image modality with user modification possible.

Ease-of-Use Evaluation

The bottom line evaluation of any radiology workstation is whether the radiologist staff can, under clinical conditions, generate acceptable interpretation reports in an acceptable amount of time. Thus, as with most tools, error rate and response time are the best objective measures of ease of use. But user confidence is also critical, for one does not want ill-at-ease radiologists who do not trust their tools. The workstation evaluator can develop a rough notion of ease of use by timing (and debriefing) a few radiologists reading multiple CT cases (or some other type of case with many images) after at least a half hour of training. But a most extensive evaluation should be conducted over a trial period of several weeks

to really learn whether that particular tool is appropriate for a particular institution's particular users performing their particular tasks.

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PACS Clinical Design Considerations

On the Probable Evolution of the Digital Environment for Radiology

Arthur F. Naylor

A.F. Naylor Co., Radiologic Consultants, Cleveland, OH

The forthcoming evolution of the digital environment for radiology can be considered as three concurrent and interacting evolutions. These are the evolution of component technologies, the evolution of system configurations and the evolution of professional and institutional usage patterns. The value of the results of the technical effort in the first two areas are significant only in the framework of the future professional and institutional utilization.

A review of the current status of the many component technologies that are involved in the digital environment indicate that in most cases, one or more additional generations of improvement are required to satisfy the future requirements of the user and of the required systems configurations. The role of diagnostically viable computed radiography for a multiplicity of examinations will probably be needed to justify the existence of a general digital environment rather than the digital environment justifying the utilization of computed radiography. For the systems configurations to achieve a general applicability within a radiology department, the system needs to progress enormously from the present status of selected modalities and limited interfaces.

The potential success and viability of this technical effort will depend upon the degree to which it can satisfy the evolving usage in the real world of radiology departments and the changing nature of the radiologist user. The usage is expected to progress from providing a radiologist with prior correlative studies, often with reduced information content, to providing the radiologist with images for original diagnosis for selected modalities, and then to providing the radiologist with images of adequate quality in all modalities for both diagnosis and demonstration. Concurrently the user can be expected to evolve from the research oriented radiologist-developer to the end point of acceptability by all radiologist users at progressively smaller institutions.

The acceptability of the future general digital environment to the institutional user and the health care system will depend upon the potential benefits of such an environment, especially in the area of the quality and cost factors relating to the digital modalities and most especially to computed radiography. The convenience factors of the digital environment can become an additional benefit after a fairly broad level of applicability is achieved. It is expected that between 1.5 and 2.5 decades will be required to evolve component technology, system technology, quality benefits, cost and usage to support routine full utilization of the digital environment.

It is believed that the successful evolution of the general digital environment will be highly dependent upon the effective utilization of computed radiography, using radiographic images in a digital format such as sensitized plate technology. Computed radiography will probably be able to provide, independent of its integration into pictorial archiving and communication systems (PACS), improvements in diagnostic quality of certain examinations based upon its wide dynamic range of radiation input, its support of new protocols of spatial and contrast post-processing, and its support of computer aided diagnosis.

If computed radiography can provide cost effective diagnostic quality benefits for a majority of radiographic examinations, then PACS, with considerable improvements in component and systems technology and in system costs, can possibly provide improved image file availability and other convenience benefits, provided that radiologists can be provided with and can accommodate feasible facilities for rapid video interpretation.

The following outline provides an evaluation of the expected evolution of component technologies, evolution of system configurations, and evolution of usage and user.

1. EVOLUTION OF COMPONENT TECHNOLOGIES

1.1 CENTRAL PROCESSING UNIT

FUNCTIONS	Data acquisition management
	Data storage and retrieval management
	Data distribution management
	RIS, HIS integration
	Management of communications with other networks or nodes
FACTORS	Archive memory transfers
	On-line, interim, cache memory transfers
	Processing speed
	Multiple processors
	Data compression & restoration (required to reduce archive storage, some transmission times)
	Selected images archived vs all images generated protocols (required to reduce archive storage)
	Redundancy, reliability, and fault sequences
	Confidentiality, security
	Work station case acquisition time

1.2 ON-LINE MEMORY STORAGE

TYPES	Daily activity memory - Centralized (may be in CPU) Daily activity memory - Distributed Interim memory - Images generated and not archived Cache memories - Queues for transfers or Queues after transfers
FACTORS	Daily activity memories New and retrieved data Centralized or distributed by modality & subspeciality Usually not compressed Cache memories - Queues for transfers between memories, especially between archive and distributed daily memories, or queues of new and retrieved data waiting interpretation

1.3 ARCHIVAL STORAGE

TYPES	Optical disk drive units Optical disk jukebox Optical tape Terabyte level units required
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1.4 DATA ACQUISITION

MODALITIES	CT, MR, US, NM, DSA, Dig Fluoro, Computed Radiography (CP) - Portable Films Computed Radiography (CR) - General	
FACTORS		
TYPE	Raw data Full reconstruction Processed data	As stored As viewed
DATA QUALITY	512x512 pixels x 8-14 bits-most digital imaging modalities 1Kx1K pixels x 12 bits - probably inadequate for radiography 2Kx2K pixels x 14 bits - probable adequate for radiography 4Kx4K pixels x 16 bits - probably not required for radiography	
INTEGRATION	Local dedicated interpretation first, then Images to PACS Single modality central dedicated processing & interpretation first, then Images to PACS Transfer to PACS before interpretation (required)	

1.5 DATA PRESENTATION WORK STATION

PURPOSE Display prior, correlative studies
 Selected modality interpretation, correlative studies
 Multi-modality interpretation, correlative studies
 (required level)
 Image display for demonstration

FUNCTIONS

DISPLAYS Multiple screens - 1, 2, 4, more
 Quality 1Kx1K pixels, 1/60 sec - now available
 2Kx2K pixels, low brightness-limited availability
 2Kx2K pixels, high brightness, required for
 radiography

PROCESSING Slow manipulation (present status)
 Medium speed processing (limited availability)
 Very high speed processing (required level)
 Rapid case acquisition time

ADVANCED VERY RAPID IMAGE MANAGEMENT & NAVIGATION

1.6 TECHNICAL WORK STATIONS - INPUT/OUTPUT

TYPES Film digitizers - Medium resolution, available
 - High resolution, available
 Hard copy printers, available
 High resolution laser printers, available

1.7 COMPUTED RADIOGRAPHY (CR) - SENSITIZED PLATE TECHNOLOGY

CHARACTERISTICS

Viable technology Independent of PACS Integration
 Wide dynamic range of radiation input
 Supports new spatial and contrast post processing protocols
 Supports computer aided diagnosis
 Inherently digital data

FORMAT

Cassettes
 Magazines
 Integrated components (chest, radiographic tables)

FACTORS

Format 2Kx2K pixels x 2 bytes
 8 MBytes/Image

IMAGE PROCESSING

Local dedicated image processing, film output-available
 Local dedicated image processing, digital output-available
 Central dedicated image processing-coming
 PACS integrated image processing-required

APPLICATION

Based on quality factors
 Based on convenience factors
 Typical sequence by exam type
 Portable, OR, chest, abdomen, GI/GU, head, spine,
 angiography, extremities, mammography
 Typical sequence by patient type
 ICU patient, pediatric, outpatient, ER satellite,
 Inpatient

(May 68)

1.8 REMOTE NETWORKS

FUNCTIONS Multilocation practices
 Teleradiology inputs - for diagnosis
 Teleradiology conferencing
 Remote demonstration - emergency rooms, operating rooms
 Remote demonstration - offices, clinics, nursing units,
 conference rooms

1.9 DATA TRANSMISSION

TOPOLOGY	Ring, star, line Integrated, multi node, distributed hubs and clusters Subnetworks, multiplexers	
TYPES	Modems Wire T-1 Line Ethernet	Fiber cable Fiber (FDDI) ANSI high speed channel Very high time-bandwidth products required

COMPRESSION Destructive - 8:1 to more
 Non-destructive - 2:1 typical for digital images
 3:1 typical for radiography

2. EVOLUTION OF SYSTEMS CONFIGURATIONS2.1 VARIOUS CONFIGURATIONS

Single digital modality
 Multiple digital imaging modality PACS
 Computed radiography local area network (requires considerable development)
 Partial radiology department PACS (requires great component and systems development, cost improvements)
 Full radiology department PACS (enormous requirements, an eventual goal)

2.2 QUALIFYING FACTORS

Digital modalities

- Transfer of adequate acquired digital data
- Feasibility of video interpretation
- Speed of video interpretation
- System functionality
- Cost

Computed radiography

- Demonstrated diagnostic quality benefits of selected computed radiography over film-based radiography
- Feasibility of video interpretation
- Speed of video interpretation
- Component adequacies and capacities
- System functionality
- Cost

Full integrated multimodality systems (radiography and digital imaging)

- Demonstrated diagnostic quality benefits of majority of radiographic exams by CR or digital techniques
- Feasibility of video interpretation
- Speed of video interpretation
- Component adequacies and capacities
- System functionality
- Cost

3. EVOLUTION OF USAGE AND USER

3.1 SYSTEMS USAGE

FUNCTION	Provide radiologist with prior, correlative studies Provide single digital modality images for diagnosis Provide several digital modality images for diagnosis Provide radiographic images for diagnosis Provide several modality images including radiography for diagnosis and demonstration Provide all modality images for diagnosis and demonstration Allow very rapid image management & navigation
USER	Research oriented radiologist-developer Selected multiple radiologists-users Acceptance of selecting reduced number of images for archive All radiologist users - selected large institutions Consensus status All radiologists users - most large institutions All radiologists users - progressively smaller institutions
TIME	Will probably require 1.5 to 2.5 decades to evolve component technology, system technology, quality benefits, cost and usage to support full utilization Partial implementation at selected institutions in the interim

3.2 POTENTIAL BENEFITS - THE PURPOSE OF IT ALL

Quality factors

Digital modalities - availability of undegraded digital data for video interpretation

Computed radiography

Wide dynamic range of radiation input

(For demanding body parts and broader technique variations)
(Radiation statistics must still be satisfied for adequate images)

Supports new protocols of spatial and contrast image processing
(For enhanced diagnosis for some examinations)

Supports computed aided diagnosis for some examinations

Convenience factors

Provides alternative to film-based film file limitations

Rapid availability of previous studies for prompt reading and prompt demonstration

Availability of same images for multiple exams and in multiple locations

Reduction of non-available films, lost films

Convenient availability of images for consultation, conferences

Provides greater flexibility in the physical location of the radiologist for interpretation of studies

(Supports modality & subspecialty specializations)

(Supports multiple locations of service)

(Supports centralized teaching environment)

(Does not alleviate need for radiologist in multiple locations to perform studies and contact patients)

Provides greater flexibility in the physical location of the referring physician for the demonstration of radiologic studies

Interrelationship of benefits

Basic PACS desirability and feasibility will derive from the inherent digital nature of a growing number of modalities including radiography

The diagnostic quality factors of computed radiography for a multiplicity of examinations will probably need to justify PACS before PACS can justify the remainder of digital radiographic examinations for convenience factors.

But, with adequate patience, it is probably much more than a house of cards built upon a foundation of smoke and mirrors.

3.3 COST VS. BENEFIT

Must be satisfied

A Quantitative Projection of Digital Environment Activity for Radiology Departments

Arthur F. Naylor

A.F. Naylor Company, Radiologic Consultants, Cleveland, OH

A detailed quantitative model has been developed for the digital environment activity within a hospital radiology department utilizing digital technology (PACS) to varying extent for different radiologic modalities and subspecialties. The information presented can either be used as a step by step guide for preparing a similar model for a particular institution or as indicative of the numeric magnitude of the required systems and the sensitivity to a number of factors and protocols.

The model includes provision for the number of yearly examinations for each of the radiologic modalities and specialties, provision for the number of images that are generated for each type of examination and provision for the digital content of each type of image. The distribution of yearly examinations is typical of a teaching hospital and the quantity is normalized to 100,000 total examinations per year.

From this data the yearly number of examinations, images and size of required digital archival memory can be evaluated for each of several levels of assumed PACS technology utilization. Five such levels of digital interpretation, archiving, retrieval and presentation are considered: 1) digital imaging modalities, 2) digital imaging modalities plus portable x-ray studies, 3) the above plus 25% of the diagnostic x-ray fluoroscopic and radiographic studies, 4) the above plus 50% of the diagnostic x-ray fluoroscopic and radiographic studies, and 5) utilizing the digital environment for all radiologic studies, including angiography and mammography.

By using this information with the results of a prior study that provides an extensive model of patient visit patterns and archive growth, retrieval and retention patterns, the analysis is extended to indicate the total daily digital activity including both generated and retrieved data.

The key factors assessed are the magnitude of the required long term storage depending upon the modalities involved and the library age for the digital storage system; and the amount of memory required for a typical days operation including both generated and retrieved data. This daily activity generates the requirements for data transfer rates and for compression and decompression processing times.

The data indicates the sensitivity of the digital systems requirements to variations in examination mix and professional protocols between institutions. The study suggests the strong desirability of the selection, at the time of interpretation, of certain images of each study for primary long term retention with the remaining images retained either for only a short period of time or retained only with high compression ratio irreversible techniques. The effects of library age and retention period are also indicated.

The following tables can be used to indicate the required magnitude of the digital archiving and retrieval activity within a hospital radiology department with a number of varying conditions and protocols, or can be used as a guide in preparing an institution specific similar model. Table 1 establishes the digital image format for each of the radiologic subspecialties and modalities and indicates a typical protocol for the average number of images per examination for each category. Table 2 shows a distribution of yearly examinations by subspecialty and modality that would be typical of a teaching hospital. This distribution is given per 100,000 examinations per year and this table and the others that follow can be scaled to any desired size of departmental activity. Based on these parameters Table 3 indicates the quantities of digital data that would be generated yearly both with and without data compression. A non-destructive data compression of 3.1 to 1 was assumed for the radiographic work and a non-destructive compression of 2.1 to 1 was assumed for the digital modalities. The table indicates the amount of digital data generated for five different degrees of incorporation of digital archiving and retrieval into the department operation. These levels are: digital imaging modalities only (ultrasound, nuclear medicine, computed tomography, magnetic resonance and DSA), digital imaging modalities plus portable radiographic studies, the previous categories plus one-quarter of and plus one-half of the diagnostic x-ray radiographic and fluoroscopic studies and a last level with all studies handled digitally.

Table 4 indicates the amount of digital data that would be generated on a typical fairly busy day for each of the levels of digital activity. Table 5 is based on prior studies of patient visit patterns and an archive growth model. It indicates the average number of previous examinations that might be expected to be retrieved for a patient who has had one or more previous visits based on different ages of the digital image library. When one is dealing with patient visit patterns and a dynamic file model it is extremely important to distinguish carefully between patient examinations, patient visits, persons per year and the number of persons or files in the library. Based upon the daily activity and the dynamic file model it is possible to calculate the quantity of generated and retrieved digital data on a typical day for each level of operation. This data is shown on Table 6. It should be noted that these quantities correspond to a yearly activity of 100,000 examinations and would be the data for just one day's operation.

Table 7 shows a summary of the total archived data and the new and retrieved digital data per day for a library age of seven years, a retention period of five years and the protocols of all images archived and all files retrieved. The indicated number of archival units required is based on an assumed capacity of 250 gigabytes for each archival unit. The daily active memory requirement, which might either be maintained in a central processing location or in several dispersed locations, is based on an individual active memory capacity of eight gigabytes. Table 8 indicates how the requirements for archival storage and daily memory for new and retrieved data grow with library age.

In order to evaluate the sensitivity of the digital requirements to changes in protocol, alternate models have been formed with the assumption that, at the time of initial interpretation, a certain number of the images generated for each exam would be designated by the radiologist as primary images. The expected number of the images that would be designated as primary for each subspecialty or modality is indicated on Table 9, together with the resulting calculation of primary image megabytes per examination. Table 10 shows the corresponding quantities of archival information that would be generated yearly with and without compression for each level of operation. It should be noted that with this protocol an additional short term erasable memory would probably be advisable for temporary retention of the non-selected images. The size of this temporary memory is based on a six day retention. Based upon this alternative protocol of archiving primary images only, the archival requirements and active memory requirements can be calculated. These requirements are shown on Table 11 for different levels of digital operation and are shown on Table 12 for different years of library age.

An additional protocol that could be considered would be to utilize mixed amounts of compression for the archiving of images. In this case it is assumed that the primary images would be stored with non-destructive compression as established earlier and the non-primary images would be stored with a non-reversible compression of approximately 20 to 1. It should be noted again that the selection of primary images needs to be made at the time of original interpretation. Table 13 shows the resulting requirements for archival storage and for daily active storage of new and retrieved data for different levels of digital operation. Table 14 shows the requirements for different years of library age.

The comparison of the long term archival requirements per 100,000 yearly examinations and for a library age of seven years with the different protocols is provided in Table 15. Similarly Table 16 provides a comparison of the daily active memory requirements for the different protocols. It can be seen that a substantial reduction in archival storage requirements and daily active memory requirements can be achieved through the use of the alternative protocols.

Table 1. DIGITAL IMAGE FORMAT

EXAM TYPE	MATRIX PIXELS	DENSITY BYTES	M-BYTES PER IMAGE	GEN. IMAGES /EXAM	GEN. M-BYTES /EXAM
DX-FL	2K2	2	8.000	8	64.0
DX-RAD	2K2	2	8.000	2.1	16.8
DX-MAM	2K2	2	8.000	6	48.0
DX-ANG	2K2	2	8.000	40	320.0
DX-PORT	2K2	2	8.000	<u>1</u>	<u>8.0</u>
DX-W/O PORT (AVE)				4.2	33.8
DX TOTAL (AVE)				3.3	26.0
DSA	.5K2	2	0.524	12	6.3
US	.5K2	1	0.262	40	10.5
NM	.25K2	2	0.131	6	0.8
CT-HD	.5K2	2	0.524	20	10.5
CT-BD	.5K2	2	0.524	30	15.7
MR-HD	.5K2	2	0.524	25	13.1
MR-BD	.5K2	2	0.524	<u>35</u>	<u>18.3</u>
DIGITAL IMAGING (AVE)				27.0	10.9

Table 2. TYPICAL YEARLY EXAMINATION
DISTRIBUTION PER 100,000 EXAMINATIONS

EXAM TYPE	YEARLY EXAMS
DX-FL	5,000
DX-RAD	45,000
DX-MAM	3,000
DX-ANG	2,000
DX-PORT	<u>24,000</u>
DX-W/O PORT	55,000
DX TOTAL	79,000
DSA (NOT PRIMARY EXAM)	
US	6,000
NM	2,750
CT-HD	4,000
CT-BD	4,000
MR-HD	3,000
MR-BD	<u>1,250</u>
DIGITAL IMAGING	21,000
SUMMARY	
DIGITAL IMAGING	21,000
DIG IM + PORT	45,000
+25% DX (FL & RAD)	57,500
+50% DX (FL & RAD)	70,000
ALL STUDIES DIGITAL	100,000

**Table 3. SUMMARY OF DIGITAL DATA GENERATED YEARLY
WITH AND WITHOUT DATA COMPRESSION**

EXAM TYPE	EXAMS	IMAGES 1000's	ARCHIVE G-BYTES	COMPR. 1Yr ARCH GBy
DIGITAL IMAGING	21,000	581.3	235.2	111.5
DIG IM + PORT	45,000	605.3	427.2	173.5
+25% DX (FL & RAD)	57,500	638.9	696.2	260.2
+50% DX (FL & RAD)	70,000	672.5	965.2	347.0
ALL STUDIES DIGITAL	100,000	837.8	2,287.2	773.5

**Table 4. SUMMARY OF DIGITAL DATA
GENERATED ON A TYPICAL DAY**

EXAM TYPE	EXAMS	GEN. IMAGES	GEN. M-BYTES
DIGITAL IMAGING	107.5	2,906	1,176
DIG IM + PORT	227.5	3,026	2,136
+25% DX (FL & RAD)	290.0	3,194	3,481
+50% DX (FL & RAD)	352.5	3,363	4,826
ALL STUDIES DIGITAL	502.5	4,189	11,436

**Table 5. TYPICAL IMAGE
LIBRARY GROWTH TABLE**

AGE	FILE YEARS	AVE. EX/RET RATIO	HIGH EX/RET RATIO
1	1.000	0.875	1.917
2	2.000	1.500	4.833
3	3.000	2.021	5.806
4	4.000	2.455	6.616
5	5.000	2.817	7.291
6	5.625	3.079	7.854
7	6.125	3.284	8.262
8	6.521	3.445	8.581
9	6.830	3.570	8.831
10	7.067	3.666	9.025
n	7.889	4.000	9.694

FOR PATIENTS WITH A PREVIOUS VISIT
RETENTION PROTOCOL: 5 YEARS AFTER DLA

**Table 6. SUMMARY OF DIGITAL DATA
GENERATED AND RETRIEVED ON A TYPICAL DAY**

EXAM TYPE	GEN. G-BYTES	RETRIEVED M-BYTES	GENFPAED & RETRIEVED G-BYTES
DIGITAL IMAGING	1.18	3.14	4.32
DIG IM + PORT	2.14	5.64	7.78
+25% DX (FL & RAD)	3.48	9.18	12.66
+50% DX (FL & RAD)	4.83	12.70	17.53
ALL STUDIES DIGITAL	11.44	30.04	41.48

YEARLY ACTIVITY 100,000 EXAMS

LIBRARY AGE 7 YEARS

RETENTION PERIOD 5 YEARS

ALL IMAGES ARCHIVED

ALL FILES RETRIEVED

Table 7. ARCHIVE AND RETRIEVAL SUMMARY - ALL IMAGES ARCHIVED

	COMPR. ARCH. GBy	NEW/ RETRIEVED GBy/DAY	ARCH. UNITS @250 GB	DAILY MEMORY UNITS @8 GB
SUMMARY				
DIGITAL IMAGING	683.1	4.32	2.73	0.54
DIG IM + PORT	1,062.4	7.78	4.25	0.97
+25% DX (FL & RAD)	1,593.9	12.66	6.38	1.58
+50% DX (FL & RAD)	2,125.4	17.53	8.50	2.19
ALL STUDIES DIGITAL	4,737.4	41.48	18.95	5.19
YEARLY ACTIVITY 100,000 EXAMS				
LIBRARY AGE 7 YEARS			ALL IMAGES ARCHIVED	
RETENTION PERIOD 5 YEARS			ALL FILES RETRIEVED	

Table 8. LIBRARY GROWTH SUMMARY - ALL IMAGES ARCHIVED

LIBRARY AGE	COMPR. ARCH. GBy	NEW/ RETRIEVED GBy/DAY	ARCH. UNITS @250 GB	MEMORY UNITS @8 GB
1	773.5	19.44	3.09	2.43
2	1,546.9	25.16	6.19	3.14
3	2,320.4	29.93	9.28	3.74
4	3,093.8	33.90	12.38	4.24
5	3,867.3	37.21	15.47	4.65
6	4,350.7	39.61	17.40	4.95
7	4,737.4	41.48	18.95	5.19
10	5,465.7	44.98	21.86	5.62
n	6,101.7	48.03	24.41	6.00

YEARLY ACTIVITY 100,000 EXAMS
 ALL STUDIES DIGITAL
 ALL IMAGES ARCHIVED

Table 9. SELECTED IMAGES FOR PRIMARY ARCHIVE

EXAM TYPE	GEN. IMAGES /EXAM	PRIM. IMAGES /EXAM	GEN. M-BYTES /EXAM	PRIM. M-BYTES /EXAM
DX-FL	8	5	64.0	40.0
DX-RAD	2.1	2.1	16.8	16.8
DX-MAM	6	6	48.0	48.0
DX-AMG	40	5	320.0	40.0
DX-PORT	1	0.4	8.0	3.2
DX-W/O PORT (AVE)	4.23	21.45	33.8	21.5
DX TOTAL (AVE)	3.25	15.91	26.0	15.9
DSA	12	6	6.3	3.1
US	40	12	10.5	3.1
NM	6	6	0.8	0.8
CT-HD	20	12	10.5	6.3
CT-BD	30	12	15.7	6.3
MR-HD	25	12	13.1	6.3
MR-BD	35	12	18.3	6.3
DIGITAL IMAGING (AVE)	27.03	4.74	10.9	4.7

Table 10. ARCHIVAL STORAGE OF PRIMARY IMAGES

EXAM TYPE	EXAMS	ARCHIVE G-BYTES	COMPR. 1Yr ARCH GBy	6-DAY TEMP. MEM "B" MB
SUMMARY				
DIGITAL IMAGING	21,000	99.6	47.2	4,068
DIG IM + PORT	45,000	176.4	72.0	9,828
+25% DX (FL & RAD)	57,500	415.4	149.1	10,728
+50% DX (FL & RAD)	70,000	654.4	226.2	11,628
ALL STUDIES DIGITAL	100,000	1,356.4	452.6	30,228

TEMPORARY SIX DAY STORAGE OF NON-PRIMARY IMAGES

Table 11. ARCHIVE & RETRIEVAL SUMMARY - PRIMARY IMAGES ARCHIVED

	COMPR. ARCH. GBy	NEW/ RETRIEVED GBy/DAY	ARCH. UNITS @250 GB	DAILY MEMORY UNITS @8 GB	6-DAY MEM B UNITS @12 GB
SUMMARY					
DIGITAL IMAGING	289.1	2.51	1.16	0.31	0.34
DIG IM + PORT	440.8	5.33	1.76	0.67	0.82
+25% DX (FL & RAD)	913.1	9.82	3.65	1.23	0.89
+50% DX (FL & RAD)	1,385.3	14.30	5.54	1.79	0.97
ALL STUDIES DIGITAL	2,772.3	30.12	11.09	3.76	2.52

YEARLY ACTIVITY 100,000 EXAMS
 LIBRARY AGE 7 YEARS
 RETENTION PERIOD 5 YEARS

REDUCED IM/EX ARCHIVED
 ALL FILES RETRIEVED

Table 12. LIBRARY GROWTH SUMMARY - PRIMARY IMAGES ARCHIVED

LIBRARY AGE	COMPR. ARCH. GBy	RETRIEVED GBy/DAY	ARCH. UNITS @250 GB	MEMORY UNITS @8 GB	MEMORY B UNITS @12 GB
1	452.6	17.05	1.81	2.13	2.52
2	905.2	20.44	3.62	2.55	2.52
3	1,357.9	23.27	5.43	2.91	2.52
4	1,810.5	25.62	7.24	3.20	2.52
5	2,263.1	27.58	9.05	3.45	2.52
6	2,546.0	29.01	10.18	3.63	2.52
7	2,772.3	30.12	11.09	3.76	2.52
10	3,198.5	32.19	12.79	4.02	2.52
n	3,570.7	34.00	14.28	4.25	2.52

YEARLY ACTIVITY 100,000 EXAMS
 ALL STUDIES DIGITAL
 REDUCED IM/EX ARCHIVES

Table 13. ARCHIVE & RETRIEVAL SUMMARY - MIXED COMPRESSION

	COMPR. ARCH. GBy	NEW/ RETRIEVED GBy/DAY	ARCH. UNITS @250 GP	DAILY MEMORY UNITS @8 GB
SUMMARY				
DIGITAL IMAGING	327.5	2.51	1.31	0.31
DIG IM + PORT	514.5	5.33	2.06	0.67
+25% DX (FL & RAD)	995.9	9.82	3.98	1.23
+50% DX (FL & RAD)	1,477.3	14.30	5.91	1.79
ALL STUDIES DIGITAL	3,054.2	30.12	12.22	3.76

YEARLY ACTIVITY 100,000 EXAMS MIXED COMPRESSION FOR ARCHIVE
 LIBRARY AGE 7 YEARS (20:1 FOR NON-PRIMARY IMAGES)
 RETENTION PERIOD 5 YEARS ALL FILES RETRIEVED

Table 14. LIBRARY GROWTH SUMMARY
MIXED COMPRESSION

LIBRARY AGE	COMPR. ARCH. GBy	NEW/ RETRIEVED GBy	ARCH. UNITS 250 GB	MEMORY UNITS 8 GB
1	498.7	17.05	1.99	2.13
2	997.3	20.44	3.99	2.55
3	1,496.0	23.27	5.98	2.91
4	1,994.6	25.62	7.98	3.20
5	2,493.3	27.58	9.97	3.45
6	2,994.9	29.01	11.22	3.63
7	3,054.2	30.12	12.22	3.76
10	3,523.7	32.19	14.09	4.02
n	3,933.8	34.00	15.74	4.25

YEARLY ACTIVITY 100,000 EXAMS
 ALL STUDIES DIGITAL
 MIXED COMPRESSION FOR ARCHIVE

Table 15. COMPARISON OF ARCHIVE MEMORY REQUIREMENTS

	ARCHIVE GBy	ARCHIVE UNITS
ALL IMAGES ARCHIVED UNCOMPRESSED DATA	14,009	56.0
ALL IMAGES ARCHIVED COMPRESSED DATA	4,737	19.0
ALL IMAGES ARCHIVED MIXED COMPRESSION	3,054	12.2
PRIMARY IMAGES ARCHIVED ALSO REQUIRES TEMP. MEMORY	2,772	11.1
YEARLY ACTIVITY 100,000 EXAMS LIBRARY AGE 7 YEARS RETENTION PERIOD 5 YEARS	ALL STUDIES DIGITAL 250 GB/MEMORY UNIT	

Table 16. COMPARISON OF DAILY ACTIVE MEMORY REQUIREMENTS

	NEW AND RETRIEVED GBy/DAY	DAILY MEMORY UNITS
ALL IMAGES ARCHIVED	41.48	5.2
ALL IMAGES ARCHIVED MIXED COMPRESSION PRIMARY IMAGES RETRIEVED	30.12	3.8
PRIMARY IMAGES ARCHIVED	30.12	3.8
YEARLY ACTIVITY 100,000 EXAMS LIBRARY AGE 7 YEARS RETENTION PERIOD 5 YEARS	ALL STUDIES DIGITAL 8 GB/MEMORY UNIT	

Operational Issues Confronting PACS: What Needs to be Done

Steven C. Horii, Seong Ki Mun, Betty Levine, et al

Department of Radiology, Georgetown University Hospital,
Washington, DC

ABSTRACT

Technology has advanced to the point at which picture archiving and communications systems (PACS) have become feasible. While it is neither inexpensive nor simple to install such a system in a hospital, a number of institutions have done so.

In our experience, the use of the hardware once installed showed a distinct time lag. Though there were those who began to use the system immediately upon receiving their workstations, these tended to be the non-radiology users. When questioned, the radiologists had few complaints about the images. Rather, it was marked differences between the way the PACS worked as opposed to conventional film reading which formed the nucleus of the dissatisfaction with the system.

Though most of these issues have been addressed with the result that use among radiologists has increased tremendously, the process of identifying the core operational differences and determining how they could be eliminated or ameliorated was very educational. In some cases, work-arounds were implemented to bypass stumbling blocks. In other instances, we had to wait until system software was updated before necessary features were available.

Occasionally, the system was used enthusiastically even though such use meant changes in operating routine. What were the incentives in these instances? Most commonly, the incentives were a time savings and reduction in frustration when compared to retrieving films from the file room.

This paper will summarize our experience in moving our PACS from a technical success to a clinically useful tool, and will describe the operational features implemented and those still necessary.

INTRODUCTION

During the past three years, we have taken the Georgetown PACS from a large scale prototype to an operational, clinically useful system. There is still a large amount of work remaining before the system can be said to have completely replaced conventional methods of operating the imaging side of a radiology department. We have learned a great deal from these three years, and will be applying what we know to the further growth of the system.

Most of the work which needs to be accomplished in order to take the system further is not in adding hardware. The development of more tailored software is far more important.

This paper will examine the system from the point of view of its major functional blocks, and will provide information on what we think is necessary for growth in each of those blocks. A schematic diagram of the Georgetown PACS is shown in Figure 1.

IMAGE ACQUISITION

The Georgetown PACS (or Image Management and Communications System - IMACS in our terminology) faced the problem of how to acquire image data from diverse equipment. The Department has two GE 9800 Quick CT machines, a Siemens 1.5T Magnetom MR scanner, four ultrasound machines (Acuson, two ATL, and Dasonics), and DuPont laser film digitizers. In order to acquire images without having to develop interfaces for each device (the ACR-NEMA Standard interface was not yet available when the system was being installed) the method of video digitization was used. This has worked remarkably well despite its limitations.¹ For ultrasound, the quality of the images has been judged to be good enough for primary reading from the workstations. Though the spatial resolution of the CT and MR images is excellent, the contrast resolution is limited to 8 bits which is insufficient for primary interpretation (unless multiply windowed images are acquired).

Our first recommendation in image acquisition is that video digitization is probably sufficient only for ultrasound imaging. The use of digital interfaces for MR and CT is highly recommended.

In acquiring images, we rapidly discovered that there is an important human element, the technologist, who must be consulted when a system will affect his or her work patterns. In earlier versions of the IMACS, the technologist had to type in a full set of patient demographics, though they discovered that they could leave out everything except the name and record number.

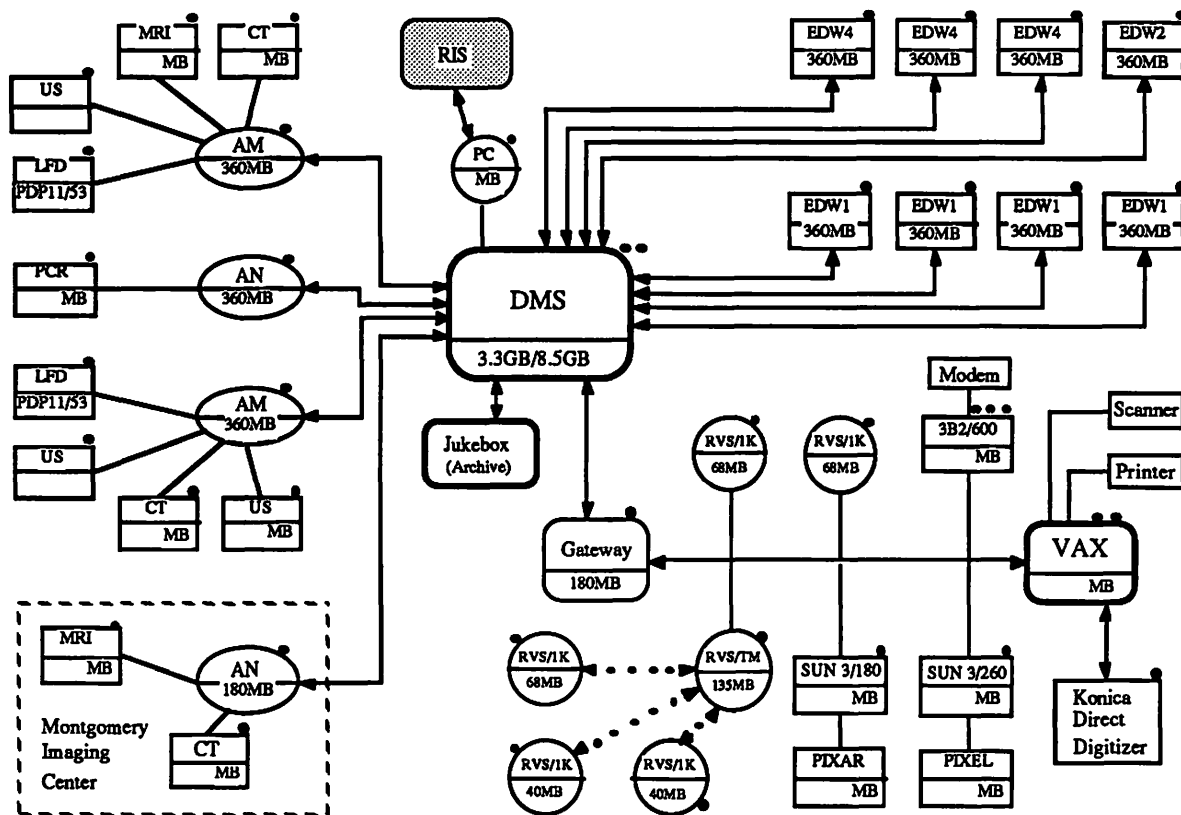


Figure 1: Georgetown University Hospital PACS Configuration

When we replaced the CT CRT multiformat camera with a laser film writer, we started receiving complaints about the speed of acquisition. The response time of the acquisition module (AM - contains the video digitizer and interface to the database manager) was longer than that of the laser camera, whereas it had been shorter than that of the CRT imager. At this point, then, sensitivity to IMACS performance was altered by a non-IMACS device. With the use of in-service training and developing close cooperation with the technical supervisors, we were able to overcome many of the technologist objections to the extra steps required to input images into the IMACS. Major advances in our favor were the improvement in AM response time with new software releases and implementation of an interface to the RIS (more on this later). Both had the effect of reducing technologist waiting time and workload.

The second lesson we learned is that the impact of new operations on technical staff must be carefully studied. If workload cannot be decreased, then the benefit and necessity of performing the additional steps must be made clear to the staff.

Most recently, because we now have workstations in multiple locations outside of radiology, we realized that getting image data from a machine is not enough. What is one to do with the data? When workstations were few in number, or infrequently used, the simple answer was to store it in a database and let it be accessed as needed, or broadcast it to all workstations. Real operations require that some selectivity be incorporated into the process. The question of how the image data is to be routed is one which affects both acquisition, since the examination type tends to be device or modality specific, and the database.

We learned from this problem (which is not yet completely solved) that the imaging equipment may have to provide some examination identification so that the image data can be linked to other information in the database.

Film digitization has been our main method for input of radiographic images. The question of whether or not the method can yield images good enough for primary diagnosis is still open. We digitize all films from the Pediatric Intensive Care Unit (PICU) and Intensive Care Nursery (ICN) as these two locations have workstations. We discovered that this process is labor-intensive, and that reliability of the hardware needed to be very high. On the plus side, we discovered that the technologists were willing to undertake this extra work partly because they discovered that they were not being interrupted as often during the day by physicians looking for films.

On the basis of our experience, if film digitization must be used (as it will have to be for input of old or outside studies) then some form of bulk-loading digitizer, which can read bar codes or other identifiers on the films, would greatly simplify this operation. A computed radiography (CR) system with a direct link

to the PACS is probably a better solution for new imaging (at least for portable and pediatric films).

IMAGE DISPLAY

For the sectional imaging modalities, such as CT, MR, and ultrasound, which generate images typically in the 512 x 512 pixel size range with 8 to 12 bits of gray scale, the displays of the present workstations are adequate. For CR images, which can be up to 2048 x 2560 pixels, the utility of a monitor which can display one-quarter of that data (1024 x 1280 pixels) has been questioned.

Display resolution issues aside, we have found that the human factors character of the workstations is a much more powerful influence on how well the workstations are accepted. If the image quality is excellent, but the process of bringing studies up on the monitors is laborious or confusing, it will take a very large incentive to make anyone use it. An example of this is with our own radiology information system (RIS) report approval process. The first pass at supporting electronic signature at a terminal was so cumbersome (if all one had to do was sign reports, the process was reasonable, but the review process also included editing the reports) that a large fraction of the staff (even those who are computer literate) refused to use the system. After the complaints were addressed, the acceptance rate improved tremendously.

There is a continuing debate as to whether the graphical user interface (GUI) is the best one to use for workstations. The majority of technical (not necessarily medical) workstations do use some form of GUI, which would lend support to the idea. We have some experience with a GUI for a workstation which we designed in-house.² This user interface was preferred over the one currently employed at our radiology diagnostic stations. The one advantage of the user interface at the workstation is that it is consistent with that used for acquisition, database access, and on the smaller PC-based systems.

We think that whatever user interface is employed at a workstation, its features should be tested in the field with attempts at doing real work. We have found that some features work well for demonstration purposes, but turn out to be cumbersome when it comes to production work.

A recurring problem we have noted is the shift in expectation when using a workstation. Timing studies we have done^{3,4} have shown that the time to bring up a case on the workstation is not very different from the time to do so from films in a jacket. The time is a bit longer for the workstation compared to a preloaded alternator when doing sequential accesses. For random retrieval, the workstation can beat the alternator. The user perception, though, is that the performance of the workstation is inferior to the film and alternator. We think that a part of this

perception has to do with the expectation which a user brings to the system. The mental model is one of "it's a computer, so it's fast". Even to those of us who understand factors such as disk access speed and bus transfer rate, staring at a blank screen seems to feel like an interminable wait. A part of the good user interface idea is to provide feedback to the user when a process will leave the display idle for some time.

Our belief is that further increases in display speed will be useful and appreciated, but that the demand for ever more speed will continue. Feedback to the user when delays are anticipated should be an integral part of the user interface.

Radiologists each have slightly different ways in which they do their reading. This is not so much inter-observer variability in interpretation, but subtle differences such things as the order in which small tasks are done or films are arranged. Residents quickly learn these preferences, and provide for them during the reading sessions.

There has been considerable discussion of the potential for such customization of workstations, but we have not seen such ideas implemented. Setting preferences based on the user log in would probably help improve user acceptance of the workstation.

The necessity of design of the reading environment appropriate to workstations has been discussed by the authors before.⁵ We have continued to see that very simple changes, such as increased work surface space and improved access to telephones, can make a difference in how comfortable it is to use a workstation. Task lighting, environmental noise, traffic patterns, and temperature and humidity control are all factors which can make a work place comfortable or impossible to use. Architects and engineers have studied such elements of work room design for years, and have more recently included designs which accommodate CRT-based equipment.

We think that a careful consideration of the environment into which workstations will be placed is essential, and that competent architectural advice should be obtained. The PACS vendors should be able to provide some assistance in this regard.

COMMUNICATIONS

The Georgetown IMACS incorporates a number of communications links. For connection between the database and workstations, and acquisition modules and the database, high-speed fiber optic links are used. These provide the high performance needed for these applications. We support teleradiology applications with two communications systems. One application, recently terminated because of the conclusion of a contractual agreement, used a T-1 service, a connection available

through telephone companies. This supports 1.544 megabit per second data transfer which is much faster than the highest speeds (19,200 bits per second) possible with current modems on voice-grade telephone lines. Voice-grade lines are also used, however, for dial-up access to the IMACS database from PC-based workstations, our other teleradiology application. For the research environment, and for supporting the PC-based workstations which are within the Hospital, Ethernet is used. It connects to the IMACS via a gateway, and currently supports retrieval of images from, but not input to, the IMACS. Video links to the acquisition devices from the imaging modalities are accomplished over analog coaxial cable, and operate at video rates. Twisted-pair lines are used for serial communication to the various text terminals supporting acquisition, display, and system control functions.

This seems to be a complicated set of communications methods to support, but this diversity has allowed us to tailor the method used to the requirement. When we have pulled fiber optic cable, we also pull an Ethernet cable so that we will have a choice of which connection to use. This has proved valuable in allowing us to exchange workstations based on evolving user needs without having to wait for a new cable run to be pulled.

The lesson we have learned is that this aspect of our PACS was properly planned, and we advocate that other systems also be able to support a variety of communications options.

ARCHIVING AND THE DATABASE

Georgetown uses a star configuration for its PACS. The archive and database computer form the center of the star. The short term archive consists of magnetic disks with a total capacity of 8 gigabytes. For reliability, this capacity is normally halved, so that the data is written to two disks (or "mirrored"). We find that this capacity supports approximately 10 to 14 days of image data at present levels of acquisition. We currently schedule movement of the data to the archive after five days, but this is a temporary measure until mirroring is re-enabled. The long term archive is an optical disk jukebox with a total capacity of 178 gigabytes. We can store more than one year's data at present image generation rates.

All of these values will be severely impacted by the input of CR images, or the expanded use of film digitization. This is because these images are so much larger in data volume than those from CT, MR, or ultrasound. We have already seen that even keeping the images in the magnetic files for a week is not long enough in many cases. For inpatients, this probably reflects the bias towards the very ill patients in the intensive care units, which have been the major clinical areas supported by the system. For outpatients, this seems to be due to the length of time of the "workup" cycle. If a patient is not very ill, the time between one examination and the subsequent one can be more than a week. The University of Kansas data⁶ would suggest ten days as a good value for storage time on short term

media. We would concur, and add that perhaps retaining data on line for the average length of stay plus some offset would be another target.

A thorough examination of the projected data volumes and an analysis of the patterns of use are important in configuring the storage component of a PACS. Erring on the side of too much capacity will certainly result in a lower frustration level among users, though it will cost more to provide this capacity.

The star design has a flaw in that it is subject to catastrophic failure if a single point, the central computer, fails. To avoid this sort of problem, the IMACS has a number of features which allow for "graceful degradation" with failures. The mirroring of the image and text data has proven highly reliable. We have had hard disk failures, but no image loss as a result. The database itself is provided with an uninterruptible power supply (UPS) to allow it to ride out short power outages, or provide time to do an orderly shutdown. We found out through a power failure that the system works, but we made one planning error. There were no terminals connected to the UPS, so though the database went on running, there was no way to shut it down properly. We solved the problem by unplugging an unused peripheral and plugging in a terminal so that a proper system shut down could be done. This procedure ties up all the computer "loose ends", so that restarting is very much simplified, and no data is lost.

Each workstation has local storage as do the acquisition modules. In the event of database failure, the workstations can still access their local data, and the acquisition modules can continue to receive images. This feature has been used, and has also contributed to the high database integrity we have seen.

The network design of our system is such that it could be converted into a fiber optic ring. This would allow other, possibly faster, protocols to be run on it. We have also allowed for spare optical fibers in the cable to be used either for expansion or replacement of defective links.

Whatever the topology of the PACS, we think that proper planning for equipment failures is a must. A careful examination of the system architecture should be done with the thought of avoiding a single-point failure bringing the whole system down. We have learned that reliability is paramount once the system is being relied on in clinical settings. Proper consideration of network design may also be used to help prevent obsolescence.

Fairly simple functions of the database can have far-reaching impact on overall system operation. An example is the change made to our mode of operation when automatic examination routing was implemented. Even with fiber optic connections, the time to transmit a CT examination of 50 slices can be long when a user is sitting at the workstation waiting for that study. For this reason, preloading the workstations with needed cases seemed to be the best way to reduce this wait.

Display from local memory is much faster than over any of the communication lines. We had our systems operator make "rounds" on the workstations once or twice daily. The list of examinations done that day was used to retrieve the studies for each workstation. The neuroradiology CT and MR exams, for example, were loaded into their workstation.

This method was labor intensive, but it worked. Auto-routing eliminated the necessity for this procedure. This feature allows the database to send examinations to workstations depending on certain selection criteria. For example, all examinations of type "US" (ultrasound) are automatically sent to the Abdominal Imaging workstation as they are acquired.

The idea of incorporating low-level rule-based "artificial intelligence" is key to user acceptance of PACS. A combination of the auto-routing feature with improved workstation speed prompted the Ultrasound Section to begin doing primary interpretation at the workstation. Prior to this, retrieving all the cases took longer than loading the films onto an alternator. A new application for intensive care unit workstations automatically displays the most recent previous examination when the current image is called up. The expansion of this idea for use in radiology should further improve user acceptance. We have done a study of the data assembling procedures done in support of radiology reading⁷, and concluded that simple, rule-based selection could equal or exceed the performance of file clerks loading an alternator. We will have to determine what the rules are; for example, when a CT examination is done, does the radiologist always want to see the previous CT of the same anatomy? Does the same hold true if the prior examination is an ultrasound or nuclear medicine procedure?

These automation concepts should be extended to retrieval from long-term storage. When a patient is admitted to the hospital, it is highly likely that he or she will have some kind of radiologic study. It is also likely that the radiologist will want to see previous films, particularly if they are of the same area of anatomy. The admission should be used to trigger appropriate retrievals from the archive, much as is done with film jackets.

Incorporating concepts of artificial intelligence and automation are very important to the growth of PACS. We have seen that adding these features makes a very large difference in the way the system is both used and perceived. If the PACS simply replaces looking at an examination on an alternator, it will be used to some degree. If it can improve performance by providing not only the requested examination, but correlation studies as well, it will find much more ready acceptance.

Much of the information needed to perform these automated functions originates outside of the PACS. Admission, discharge, and transfer information usually comes from the HIS. Procedure scheduling and results reporting are often

handled in an RIS. An interface to these systems is an integral part of establishing an operational PACS.

Our HIS includes RIS features, so we are fortunate in having to establish only one interface. This effort required about one full person-year, but the result has been very useful. At present, the interface is one-way, and the IMACS accepts examination requests directly from the RIS. A PC is used both as a protocol converter and filter, since we do not acquire all radiographic studies on the system, only pertinent requests are processed and sent to the IMACS. The incoming request information is converted into an ACR-NEMA data set for transmission to the IMACS, but uses RS-232 hardware and protocol rather than the full ACR-NEMA interface. The data set contains a fairly small amount of information, since it does not have image data to transmit. The RS-232 link is not a bottleneck for transfers.

The end result of capturing the request information is that it eliminates most data entry by the technologists, who now only have to type in the patient name or medical record number. The rest of the demographic information is retrieved from the RIS. In addition, other data in the request can be used to support auto-routing.

The next phase of the RIS-IMACS interface operation will be to retrieve reports. In this way, the images and reports will be accessible from the workstations. We are also interested in having the IMACS accept edit transactions from the RIS. The primary interest in these is to correct database entries in the IMACS. The most frequent change is that issued to correct the patient name. In the ICN in particular, babies may be admitted with no given name, so the system shows them as "Doe, babyboy or Smith, babygirl". If they are given names while still in the ICN, they still retain the same medical record number, but the HIS updates the name file. This causes problems when received by the IMACS, which will flag an error unless its patient data file has also been edited. This is currently done manually.

The efforts of ACR-NEMA Working Group VIII, which is addressing standardization of HIS/RIS/PACS interfaces, should be most useful in helping solve the problems of such interfaces. We would recommend following their efforts, and when it becomes available, adopting the standard practice.

COSTS

The Georgetown IMACS development was done under a contract with the U.S. Army and MITRE Corporation, and was known as the digital imaging network (DIN) project. During the contract period, which ended in January, 1990, most of the costs of the system were covered by the contract.

As the DIN contract has been concluded, we are faced with the problem of how to expand the system to provide further clinical use. We have seen that support

from the physicians outside of Radiology is going to be very important to the further growth of the IMACS. Our work with the pediatricians has shown us that the support can be substantial. While we cannot yet have any of the system overhead reimbursed from third-party payers, we can reasonably ask the Hospital, or specific departments, to help support hardware located outside of Radiology. We still do not know if this idea will be successful, but if the system can provide real utility, and if the physicians are vocal enough in asking Hospital Administration to support the system, we stand some chance of relieving a part of our operational expense.

What we have seen to be essential is the enthusiastic support of the non-radiology users of the system. A PACS which operates so as to earn that support will have a better chance of success than one which supports only radiologic operations.

CONCLUSION

While we have made progress in transforming our PACS into a clinically useful system, there have been a number of difficulties to overcome. We think that developments in the areas of human factors for the workstations, improved automation and artificial intelligence applications, and the growing use of standards will all contribute to making the next generation of PACS much more inviting and easy to use.

ACKNOWLEDGEMENT

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Operational Strategies for Optical Archives

Marcus W. Hedgcock, Jr., Suzy Smith and Tod S. Levitt

Center for Computed Imaging, San Francisco VA Medical Center,
San Francisco, CA and Department of Radiology, University of California,
San Francisco, CA

Introduction

The purpose of PACS (Picture Archive and Communication Systems) is to improve the storage and distribution of medical imagery. Large format optical archives are being developed to contain one terabyte or more of medical image storage. The goal is to provide storage of at least two years worth of medical imagery and to serve multiple users via Wide Area Network (WAN) and Local Area Network (LAN) image transmission and electronic diagnostic workstations. Optical archive search and retrieve algorithms (and the mechanical portions of the search) are relatively slow. Also, the volume of each data set is large enough to impair transmission throughput on even the fastest LAN or WAN network. The effectiveness of these optical archives depends on data storage format, system configuration and on the schemes (including compression) which are developed for storage, retrieval, and transmission of data. To date, however, little has been published on operational protocols which will make an optical archive workable in real-time in a networked clinical environment. The goal of our institution is to develop a networked "filmless" medical imagery environment over the next three years. To this end, we have developed a set of operational protocols for archiving and retrieving of medical imagery from an optical archive linked, or more accurately bridged, to local area networks (LANs) of workstations and integrated with the Radiology and Hospital Information Systems. These protocols minimize search time for images (both by the system and by human operators), retrieve projected image needs from the optical archive during off hours, and relay them to intermediate term memory in the appropriate LAN. The protocols decrease access time for the clinician and radiologist and decrease traffic on the optical archive for emergency requests.

Purpose of a Medical Imagery Archive

The purpose of a medical imagery archive, regardless of mechanism, is to accept new imagery, store the imagery securely, and distribute the imagery to facilitate patient care. Electronic archives offer several improvements over the current film and shelf system including decreased space requirements, decreased loss of imagery, more rapid access to imagery, and (possibly) decreased need for archive personnel. Although cost is also an important consideration, the relative cost is difficult to project because of changing costs for each segment of the archive. Continual increase in recurring cost for space, film, and "low-level" archive personnel with concomitant decrease in the cost of computers and storage media suggest, however, that electronic archives will soon be more cost-effective than the current system.

Flow of Medical Imagery

Medical imagery used for medical care is distributed to patient care, imagery acquisition, and conference locations, both within the medical center and at remote medical facilities involved in a patient's care. The features of this distribution pattern are shown graphically in Figure 1.

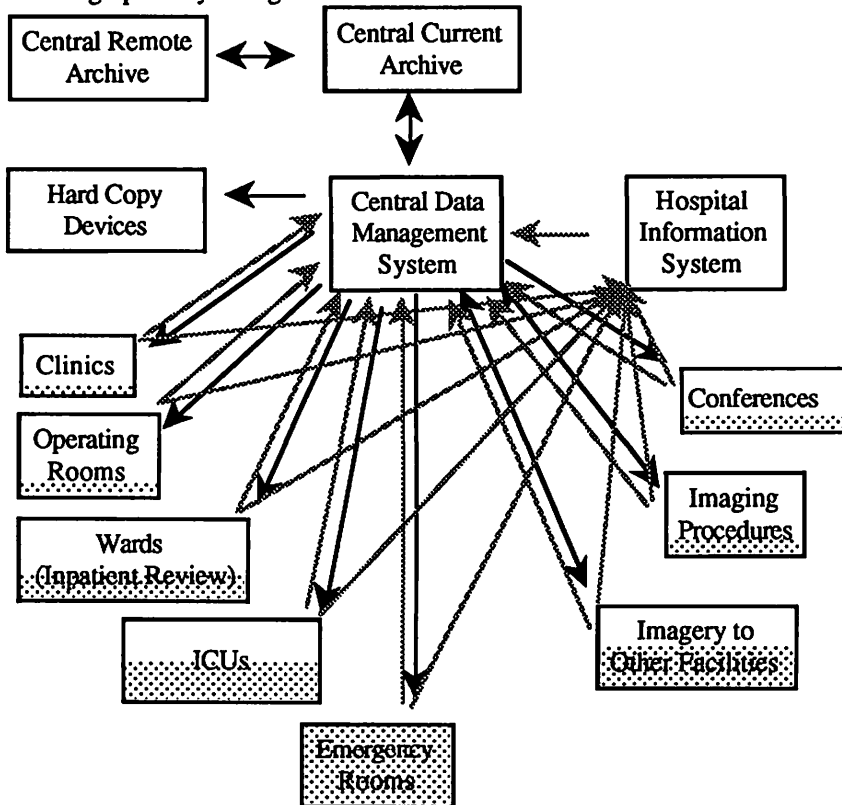


Figure 1 - Medical Center Imagery Distribution - Imagery is requested (gray arrows) from various locations within and outside of the medical center, and the imagery is distributed accordingly (black arrows). Most of this imagery transfer is scheduled in advance through the Hospital Information System network. A smaller amount of imagery (shaded sections of the boxes) is requested on an ad hoc basis. The quantity of ad hoc requests varies with the location function. Some locations (double black arrows) generate additional imagery for the archive.

The term imagery is used because electronic imagery storage and transmission allows us to include imagery in our archive other than that traditionally thought of as medical images (x-rays, magnetic resonance scans, etc.) such as real-time ultrasound, clinical pathology slides, anatomic pathology slides, retinal photographs, etc.

The picture is less confusing (Figure 2) if we consider that there are really only two types of requests for imagery made from the archive: scheduled and ad hoc (unscheduled).

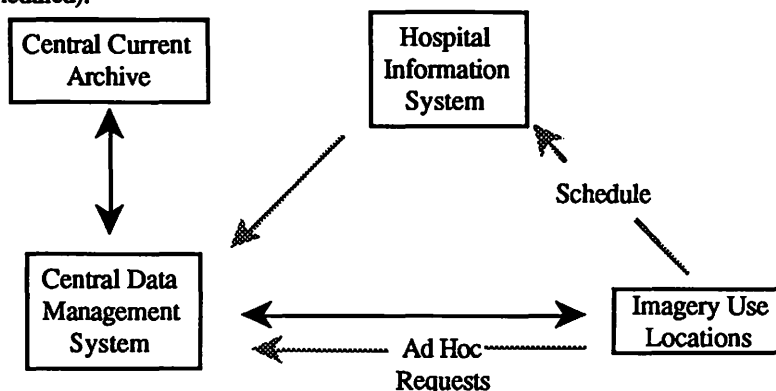


Figure 2 - Requests to distribute imagery from a central archive to locations are either scheduled through the Hospital Information System, or as ad hoc requests throughout the day.

Although Figure 2 shows all scheduled requests routed through the Hospital Information System, some scheduled requests (conferences, etc.) may go directly to the Data Management System. The important point is that scheduled imagery retrieval and distribution can be done outside of peak operational hours.

Volume of Imagery and Percentage of Scheduled vs. Unscheduled Requests for Imagery

As we have noted before [2][3], electronic handling of imagery has some limitations. We cannot transport the same volume of data as with film storage. For example, a rough calculation shows that our file clerk moving the carts of radiographs to the clinics is moving the data at 2,133 megabytes per second. Available electronic systems cannot compete with this. Not all of this transported data is actually used. The patient's entire film jacket is sent to each location, but only a few of the images in the jacket are actually used.

To estimate the volume of data we will need to send electronically, we analyzed the film distribution to each location in Figure 1, and the percentage of requests scheduled the previous day. We also determined how many images of those sent were actually used at each location.

Table 1 shows the quantity of imagery in megabytes requested from our archive at SFVAMC and sent each day to the locations in Figure 1. We use a combination of film and electronic storage and distribution; these figures were obtained using a conversion of 6 megabytes per film, which we have shown previously¹ gives an accurate projection of electronic volume.

TABLE 1

Location	Sent	Used	% Sched	MB Sched	MB Unsched
Conferences	3,600	1,080	95%	1,026	54
Clinics	48,000	9,600	98%	9,408	192
Imaging Procedures	33,600	8,400	82%	6,888	1,512
Operating Rooms	2,400	480	90%	432	48
Wards	8,880	1,332	75%	999	333
ICUs	3,600	270	50%	135	135
Emergency Rooms	9,600	960	0%	0	960
Other Facilities	3,600	720	40%	288	432
DIST. SUBTOTAL	113,280	22,842	84%	19,176	3,666
New MC Imagery	2,400	2,400	0%	0	2,400
New Outside films	960	96	0%	0	96
NEW SUBTOTAL	3,360	2,496	0%	0	2,496
TOTALS	116,640	25,338	77%	19,464	5,874

The second input to the system is new examinations. New examinations for the system (Figure 3) represent both exams done at the medical center and outside the medical center. If we add the outpatient exams, with comparison imagery, the total sent rises to 116 Gigabytes, but only 25 Gigabytes (about 21%) was used.

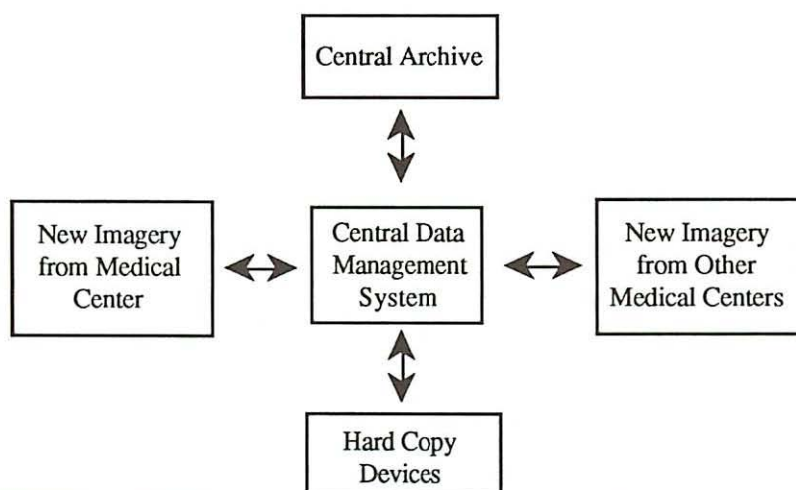


Figure 3 - New Examination Entry into PACS

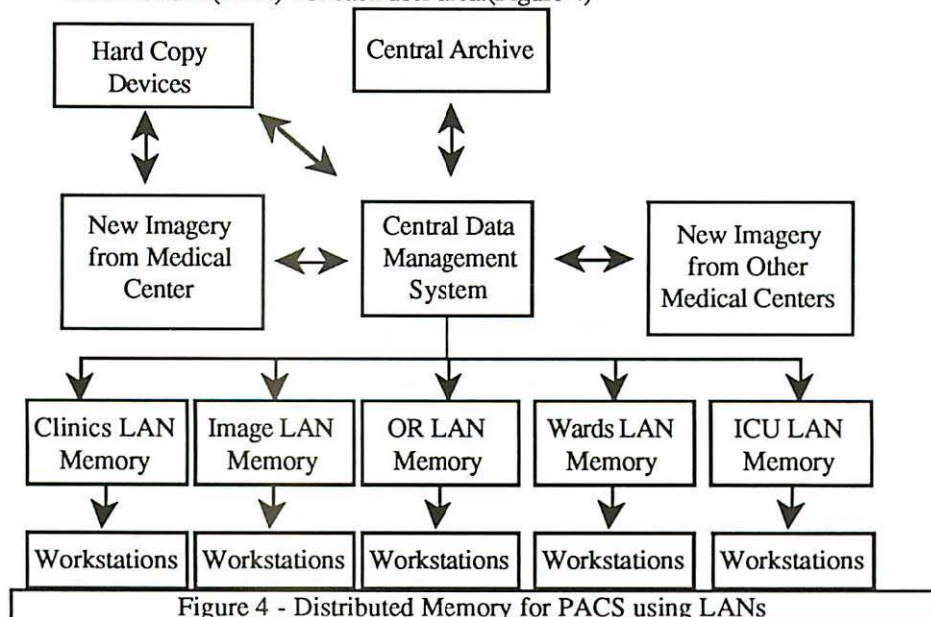
Several important observations emerge from the study results in Table 1. Note that in the distribution subtotal we sent out 113 Gigabytes of data to the various

locations, but only 23 Gigabytes were actually used. Overall 84% of the data to be called from the archive and transmitted is known the day before (new exams obviously do not have to be called up from the archive), although some locations like the emergency room requested all of their imagery on an ad hoc basis. If we can determine the imagery which will be used, we can limit the short term memory requirement in the system for archive and new imagery to about 26 Gigabytes for the exams to be distributed

The Strategies

With knowledge about how imagery is currently introduced and distributed within the system, strategies can be applied to minimize the limitations of an electronic system.

1. Imagery can be grouped on storage units in the archive. Grouping imagery decreases the seek time for the system. We have shown^{[3][4]} that the best method is to archive by a random number assigned to each patient. We advocate the last four digits of the social security number which is already assigned and acts as an image identifier as well. Although this system can be used with a single unit device like a single platter optical archive, a multiple unit device (such as an optical platter jukebox) is required for effective clinical operations.
2. We can take advantage of distributed short term memory by developing a local area network (LAN) for each user area.(Figure 4)



This distributed short-term archive plan also frees up the central Database Management System for processing of new imagery being added to the system and ad hoc requests.

3. Since 84% of the imagery is requested in advance, this imagery can be extracted from the long-term archive at night, and be immediately available in the short-term parts of the network. Since the majority of these cases reflect patient scheduling in the HIS, instructions can be sent to the PACS and archive from the HIS to move the cases into short-term memory.
4. Only the cases to be used should be moved into short-term memory. Although needs and desires of clinicians and radiologists may differ slightly from center to center, decision rules can be fairly easily set up so that only the most recent examinations with appropriate numbers of comparison images are retrieved and sent^[5].

Summary

Electronic archives have great promise to improve medical care by increasing access to medical imagery and eliminating lost images. Certain limitations of electronic archives can be eliminated or minimized by development of local area networks (LANs) and operational protocols to retrieve only needed imagery and to retrieve scheduled imagery outside of peak hours.

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Database Requirements for PACS Workstations

Marcus W. Hedgcock, Jr., Suzy Smith and Tod S. Levitt

Center for Computed Imaging, San Francisco VA Medical Center,
San Francisco, CA and Department of Radiology, University of California,
San Francisco, CA

San Francisco VA Medical Center is conducting a pilot project to complete conversion to digital imaging services within the next five years. Our Computed Imaging Group at SFVAMC has directed efforts toward PACS development¹⁻¹⁵ to plan for system expansion and guide the evolution of these systems. For it to be efficient, a large amount of information from the Radiology and Hospital information systems must be available to PACS. Some of this information is permanent, such as patient identifiers, however a large amount of the information used to route, read, and communicate the results of images is transient. We present various storage and network solutions to provide this information on PACS, allowing PACS to improve radiology operations, rather than merely emulating current practice.

Introduction

PACS offers potential improvement for the storage and distribution of medical imagery, but presents some new limitations as well. The large amount of data in medical images (a PA and lateral chest radiograph requires about the same amount of data space as the first four volumes of the Britannica) means that a patient's entire imagery file cannot be transmitted each time a new image is interpreted or an image is reviewed. In addition, a large amount of ancillary information is needed for effective use of medical imagery in clinical practice.

Use of Imagery at Four Representative Centers

To determine current imaging operation methods, we studied practices at four medical centers in the San Francisco Bay Area⁵. We then used this data to extrapolate the on-line storage and functions required for effective PACS. The centers reviewed were a) San Francisco VA Medical Center [SFVAMC], a medium-size Federal facility with academic affiliation; b) the University of California Medical Center [UCSF], a large university medical center; c) San Francisco General Hospital [SFGH], a medium-size county hospital; and d) Merritt-Peralta Medical Center, (a medium-sized private medical center).

At each center, we identified a) the case compilation process, b) distribution of cases to reading areas, c) the need for prior imagery, d) prioritizing of images to be read, e) ancillary information used in conjunction with image interpretation, f) the transcription process and other sources of interpretation information, g) how images

were identified as having been interpreted, h) the fate of interpreted examinations, i) how images were sent to other institutions, and j) the construction of teaching files.

COMPILATION OF CASES

At all centers, cases were compiled in the file room area by matching the new imagery with the patient's film jacket or jackets. Stat cases were placed at the top of the stack and given priority. Matching was done by using the identifiers on the imagery and the patient's jacket. Cases from outside the medical center were searched separately to identify whether the patient had a file within the medical center. The contents of the film jackets varied at each institution. Some institutions had separate file areas for plain films, CT, ultrasound, MRI and nuclear medicine. In others, the film jacket contained plain films, CT and MRI, but not nuclear medicine, etc.

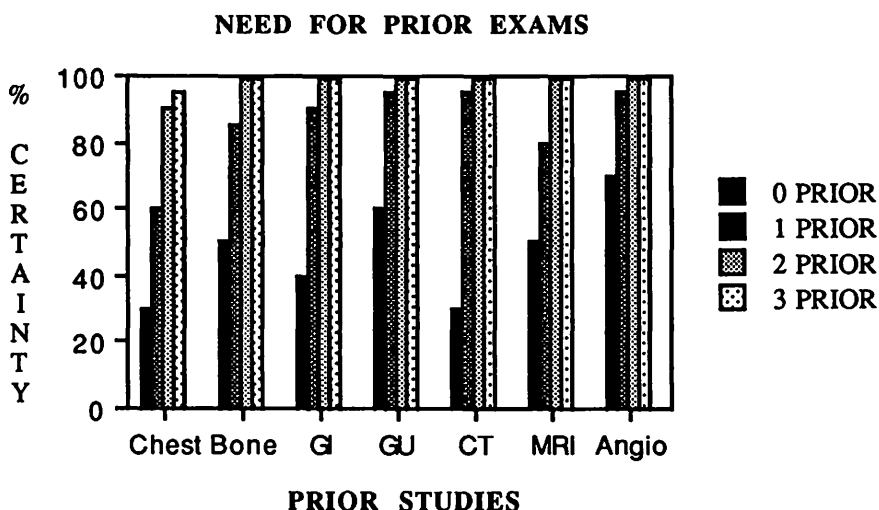
DISTRIBUTION OF CASES TO READING AREAS

At each institution, reading areas were separate and cases to each reading area were divided according to type of case. At all four institutions, cases tended in general to be distributed according to modality: plain film cases to one reading area, CT to another reading area, etc. The larger and "more academic" the institution, the more subdivided the cases became. At the University of California, San Francisco, for example, plain chest x-rays and bone x-rays each went to separate areas.

NEED FOR PRIOR COMPARISON IMAGERY OF SAME TYPE

The relation of confidence to number of prior images used to interpret each examination is shown in Table 1.

Table 1 - Confidence Level and Number of Prior Exams by Type



Both radiologists and clinicians tended to use more prior examinations when reviewing chest radiographs compared with other types of examinations. If available, at least one single previous examination was always, and using additional previous examinations was common. For chest examinations, two to three sets of prior

examinations were often used by the image reviewers, and confidence levels increased with the number of prior exams available.

PRIORITIZING CASES FOR INTERPRETATION

Most images were interpreted on a first in, first out basis. Interrupting the queue and moving cases to first priority was common. Requests for these exceptions came from a specific area, such as the emergency room, on request of a physician as part of the exam request, or on an ad hoc basis by telephone or other contact.

ANCILLARY INFORMATION FOR IMAGE INTERPRETATION

At all four centers, additional information (besides the comparison imagery of the same type) was used in the review and reporting process. The most common information used is outlined in the examples below.

Recent examinations of the same body part done on a different modality were commonly used. Most frequent were referral to chest CT while interpreting a plain chest x-ray (and vice versa), and referral to a nuclear medicine bone scan while interpreting a bone x-ray (and vice versa).

Information from the patient's clinical record was commonly used as an adjunct to interpretation, for example, pulmonary function tests or patient temperature in conjunction with chest x-ray interpretation. The radiologist generally called the referring clinician to obtain this information, rather than accessing the clinical record directly.

Information from the study request and/or the Hospital Information System database was used in a large number of cases to contact the referring physician or ward staff to impart or get further information, or to call the patient back for further images.

TRANSCRIPTION

At all four centers, interpretations were dictated for manual transcription into the Hospital Information System database. No centers used voice activated transcription. At all centers, other sources of interpretation information were maintained. These included written abbreviated reports on the front of image jackets, notes in inpatient charts, and for several modalities and specialty examinations, a separate log book with a chronological list of interpretations.

IDENTIFICATION OF INTERPRETED IMAGERY

Examinations at all four institutions were identified as interpreted by the absence of a paper request, a written interpretation on the front of the image jacket and/or a written report in the specialty log book mentioned above.

FATE OF INTERPRETED EXAMS

At all institutions, standard outpatient examinations were returned to the archive, unless the interpreting radiologist had set the case aside for further review or consultation. Inpatient exams and specialty examinations (CT, angio, etc.) tended to remain on reading boards for 1 to 5 days to facilitate the consultation process.

EXCHANGE OF IMAGERY WITH OTHER INSTITUTIONS

At all four institutions, imagery was exchanged in the form of hard copy, usually duplicates.

CONSTRUCTION OF TEACHING AND QUALITY ASSURANCE FILES

At all four institutions, teaching and quality assurance files were constructed in one of two ways. Cases were either flagged at the time of interpretation, or a search was made through the specialty log book for cases which met the search criteria. No institution had a database search capability for interpretations within the Hospital Information System.

Implications for PACS

1. There must be a means to segregate of cases by type and transmit these cases automatically to the appropriate reading areas. This distribution scheme must be easily tailored to the specific institution and to changes in section activities within that institution.

2. Automatic protocols must exist in the data management system or archive for retrieval of only those comparison images which are deemed necessary at that institution for image interpretation and/or review.

3. A mechanism must exist to flag priority cases and put them first in the interpretation queue. The physician at the workstation must be able to adjust the queue for ad hoc priority requests.

4. Ancillary information from the patient's file must be readily available at the workstation. These include a) other modality studies, b) identifiers for the exam and patient, and c) other ancillary information.

a) Other modality studies: The user should be able to call up other modality studies rapidly from the patient's imagery file to assist with interpretation. A mechanism should exist to include other modality studies automatically, if these studies are commonly used and meet the criteria for inclusion (e.g. for chest x-ray interpretation, the most recent chest CT if done within 3 months). The criteria should be easily adjustable by the system manager to meet the needs of the users at each institution and section.

b) Exam identifiers:

1. Patient name (Last, First)
2. Patient ID # (National ID #, Country)
3. Hospital ID # (if different from 2.)
4. Patient Date of Birth
5. Date of exam
6. Time of exam
7. Modality (Generic type, Vendor, Location)
8. Exam type
9. Images in this exam
10. Center where examinations were done

c) Other patient/exam information:

11. Priority
 - a) routine b) stat
 12. Interpretation status
 - a) Uninterpreted b) Preliminary interpretation c) Final interpretation
 13. Patient contact information
 - a) Current location b) CL address & tel c) Home address & tel
 14. Referring or ordering physician information
 - a) name b) contact address/location c) contact telephone
 15. Attending physician information
 - a) name b) contact address/location c) contact telephone
 16. Ordering service information
 - a) name b) contact address/location c) contact telephone
 17. Area of origin of request information
 - a) name b) contact address/location c) contact telephone
5. The workstation/PACS should allow groups of cases to be developed for various clinical functions. These "case lists" must be easy to develop and use, but access and/or modification of them must be restricted to certain classes of users. These groups or lists fall into the following categories:
- a. transient one-time (ad hoc conferences)
 - b. transient recurring (patients' imagery for specific clinics and OR)
 - c. transient evolving (inpatients for daily rounds)
 - d. permanent (teaching file, quality assurance)
6. The workstation should offer capabilities beyond the standard alternator. Possibilities include:
- a. Free text search of all interpretations in the HIS database
 - b. On-line image and text clinical and anatomic pathology data
 - c. On-line imaging/medical literature
 - d. On-line teaching file
 - e. On-line list of medical center and appropriate telephone numbers
 - f. Voice-activated transcription
 - f. Routing of exams by user to another user or workstation at the same or a different institution

Implementation Considerations

Considerations for implementation include interfacing the sources of the raw data for the database, adequate RAM and/or rapid access to intermediate and long-term archives to hold the data, methods to update transient information associated with the imagery, and maintenance of data and database security and integrity.

SOURCES OF RAW DATA

Raw data sources include:

- a. Digital imagery
- b. Digitization of non-digital imagery
- c. Radiology information system
- d. Hospital information system

- e. Other computer databases
- f. Input from users

RAM AND/OR ACCESS TO INTERMEDIATE/LONG-TERM ARCHIVES

Adequate aggregate network RAM must be sufficient to allow rapid access to the appropriate information at each workstation. Alternatively, increasing the speed of access to long-term archives and data retrieval from associated computer networks such as the HIS would give the illusion of on-line data.

UPDATING OF TRANSIENT PATIENT/IMAGERY ASSOCIATED DATA

The information which the user receives at the workstation must be correct. Transient information, such as patient location, must be updated in a timely fashion.

DATA AND DATABASE SECURITY AND INTEGRITY

There must be a method of limiting access to certain parts of the database. In addition, the ability to modify the database, (e.g. to construct lists, add to transient or permanent files) must be restricted to certain classes of users. We may also wish to restrict to certain users the capability to generate ad hoc reports and/or hardcopy.

Problems to Solve

Problems to solve include:

1. Development of dependable and rapid interfaces to import unmodified imagery into the PACS.
2. Duplication of modality-specific workstation functions at PACS workstations.
3. Inclusion of non-standard medical imagery (e.g. pathology slides, retinal photography, etc.) in PACS imagery database.
4. Automatic updating of all transient files associated with the imagery.
5. Easy assignment and modification of user access and automatic image routing.
6. Transparent interface of PACS workstations to associated information networks, including HIS, other text databases.
7. Continuous user feed-back to evolve system for maximum functionality.

Summary

PACS has the potential to expand the utility and availability of medical imagery. Although computers and computer storage capable of using medical imagery in ways exceeding the limitations of the lightbox system are available now, these capabilities must be offered in a fashion which emphasizes ease of use and a short learning curve for the technology to be widely accepted. Attention to completeness of the database needed for medical imagery use is important. With a complete database we can apply artificial intelligence techniques to increasingly automate the PACS environment.

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Objective Driven Concepts Applied in a PACS Project

R. Kanz, A. Aouati, V. Hennebel, et al

Centre de Recherche Public Henri Tudor, LUXEMBOURG

J. Duchene and J.F. Lerallut

Universite de Technologie de Compiègne, FRANCE

R. Dondelinger and J.C. Kurdziel

Centre Hospitalier de Luxembourg, LUXEMBOURG

Abstract:

In this paper, we present a PACS project and the related concepts developed by three teams: a medical group and engineers from two technological research centers.

The bases of our work are the medical requirements expressed by the radiologists to improve the radiology department by new technological tools.

Our aim is to end up with the functional multimedia network environment with special emphasis put on the user oriented interface for the different kinds of working or viewing stations.

The multimedia aspect involves an association of images, speech and text data allowing to store, in an original way, images and interpretation together as a non separable entity.

During the first step of the project concerning preliminary studies and developments, a prototype workstation is being realized and original concepts for image compression have been carried out.

All technological choices are made to keep the environment able to follow the evolution of products and standards.

1. Introduction

The need for a Picture Archiving and Communication System at the Centre Hospitalier de Luxembourg (CHL) has been expressed initially by the physicians of the Radiology Department in 1987. Because no commercially available ready-made system was in agreement with the medical requirements of the radiologists and was open enough, a collaboration with research centers was decided to develop a home-made PACS based on existing industrial standards.

After describing the environnement of the project and the team working on it, our approach of the PACS and the difficulties that can rise will be presented. Then the concepts developed for the different components of the PACS will be discussed.

2. The hospital and the PACS team

With a capacity of 500 beds, the Centre Hospitalier de Luxembourg is the largest in the country. Since its opening, the CHL has been playing the role of reference center for other hospitals in Luxembourg. According to this policy, a project of installation of a Picture Archiving and Communication System was decided upon the request of the radiologists of the CHL. Their arguments for the installation of a PACS are:

- more diagnostic information are extractible from the digital image;
- the retrieval of previous exams is easier;
- the costs are better controlled;
- the efficiency of the department is improved.

Every year 48,000 patients are treated and 125,000 procedures are realized in the Radiology Department. The already available digital imaging modalities are one CT Scanner, one DSA unit, several ultrasound machines and one nuclear medicine unit (outside the departement). A new building is being built to install a second CT Scanner and a DSA unit in 1990, as well as a MRI unit. Within the next 4 years, digital radiology units will replace the existing conventionnal devices.

As more and more modalities are digital and because the departement is being split over two different geographic sites, the PACS concept becomes very attractive and an image network will be necessary. The extension to other departments within the hospital will also be considered as clinicians are interested in the use of the PACS. The CHL pilot project experience and the PACS knowledge gained during the study will help to diffuse such systems to smaller hospitals across the country, allowing ISDN teleradiology applications like expert consulting (7, 8).

To satisfy the clinical expectations expressed by the medical group, custom-made developments have to be realized. The CHL team providing the medical input is composed of members of the medical and administrative staves. The scientific partners are the Biomedical Department of the University of Technology of Compiègne (UTC, France) and the Public Research Center Henri Tudor (CRP-HT, Luxembourg) that has R&D activities in the fields of image processing, networking, software engineering, microelectronics... . A management committee composed of members coming from the CHL, the UTC and the CRP-HT has been created. An important task of the comittee is to promote the cooperation between the technical and medical communities. The three partners also participate in the management group of the european

PACS project ISCAMI (Integrated Systems of Computer Assisted Management and Manipulation of Medical Images).

3. PACS approach and working plan

The PACS project at the CHL is based on the medical requirements to improve the Radiology Department by applying new technological tools. During the top-down approach, the clinical expectations of the PACS and the conditions for optimal implementation at medical, technical, financial and organizational levels have to be defined. A statistical analysis of the department is being performed to obtain a precise view of its activity. Special emphasis has to be put on the designing of user oriented interfaces for the radiologists (5, 9). The analysis of previous PACS experiences in other countries is also important, as well as documentation studies and participations to international meetings in this field of research.

Localized PACS modules are also developed in a bottom-up approach. Among the different realizations which will be integrated in the final system, the development of prototype work- and viewing stations with friendly user interfaces is a major point of our study. A ROC study on resolution has been developed and is now at the clinical evaluation level. Other tasks concern the acquisition of images from digital imaging modalities or from a film digitizer, the study of the ACR-NEMA protocol, the installation of a Radiology Information System related to PACS, the evaluation of X-ray sensitive CCD camera for digital radiology... .

Two phases have been clearly distinguished for the realization of the PACS project:

- the phase I composed of several tasks concerning the preliminary studies and developments for 16 months,
- the phase II for the realization of the PACS at the CHL between 1991 and 1995.

At the end of phase I, the feasibility of the PACS will be determined from the results of the different tasks and the committee will decide if the phase II can start.

At the time the abstract was sent, the phase I was programmed to be shorter. Because the collaboration between the medical and the technological communities has not been always easy, the project had to be redefined and the first phase extended. We hope that the stability of the partners will be reinforced by the creation of the management committee.

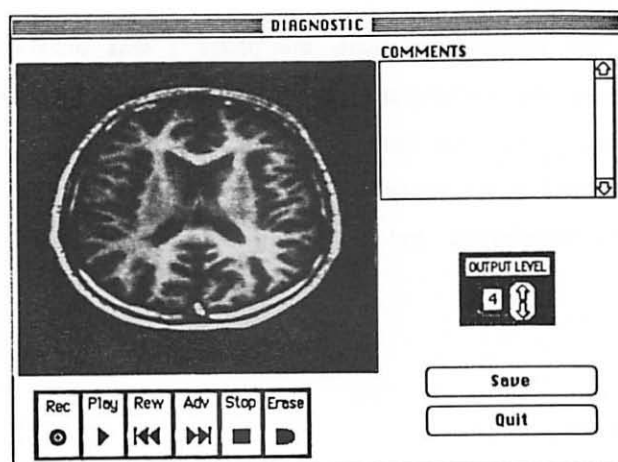
4. PACS Components

4.1. Working and Viewing Stations

The conceptual study in this field has led to the distinction between two types of stations: the workstation for the radiologist who produces the diagnosis and the viewing station for the clinician and the radiologist for consulting purposes of their patient examinations (9). Their features differ greatly when the required processing abilities are compared. The radiologist needs image processing tools such as distance and density measuring, contrast and edge enhancement, reverse gray scale, zoom and some histogram manipulations (3). In

order to avoid the development of non-functionnal stations the number of these tools must be limited. Powerfull hardware is necessary and a Sun 4-330 GPX workstation with a VME Bus will be chosen. Two to four high resolution screens (2000x2000 pixels) will be used for multimodality purposes and to allow the display of the entire set of images necessary to diagnose.

PC's or Macintosh II with an additional high resolution screen can be used for the viewing stations.



At the present time, a user interface using the X-Window protocol is being developed on a multimedia Mac II cx with the Unix operating system. Figure 1 presents a prototype interface for the radiologist. As the image is displayed, the diagnosis can be vocally added with usual keys activated on the screen by a mouse (record, rewind, fastforward, play...). The vocal comment (digital form) can also be synchronized with a cursor underlying the pathology on the image (this possibility also presents some interest for tutorial purposes).

After validation of the diagnosis by the radiologist, the image and the interpretation will be send on the network to the medical secretary. As no efficient speech recognition system has been designed yet, the interpretation is synthetized and then typed by the secretary as text data. The complete exam composed of images, text and speech is digitally archived as a unique entity according to the ACR-NEMA standard (1).

Because the acquisition of the Sun station will not occur until phase II, the application will be transfered to a Sony NWS 1750 or a HP 9000 available at the CRP-HT and connected to the Mac II Cx. The transportability is enhanced by the use of standards (Unix, X-window, ACR-NEMA, NFS ...).

The development of work- and viewing stations with friendly user interfaces defined with the radiologists is our major concern to facilitate the transition from the lightbox to the stations.

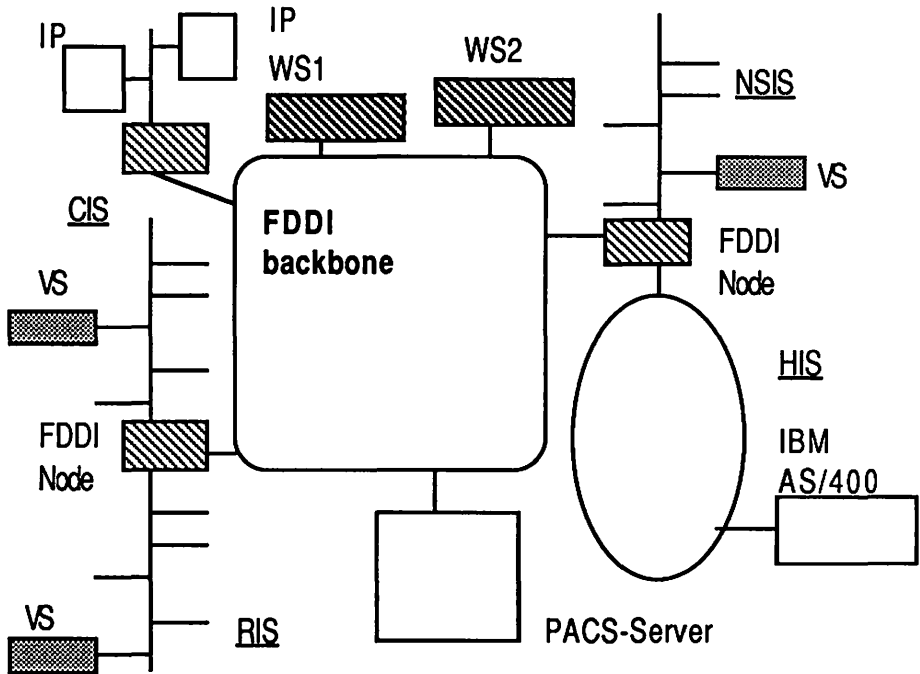
4.2. Architecture and Network

Figure 2 shows the final configuration of the PACS at the CHL as we conceived it.

A distributed architecture has been prefered with local archiving at the imaging modalities. This solution permits a more flexible management and increases the reliability of the system against breakdowns. The storage units are composed of juke-box and optical disks for on-line and long term archiving (2).

The backbone of the system will be a FDDI network (10) where the imaging modalities and the workstations are directly connected to provide high speed communications. Local Ethernet or Token Ring networks for the administrative management (HIS, RIS...) in the

different departments of the CHL will also be linked to the FDDI backbone. The HPMS running on the IBM AS/400 mainframe of the CHL manages those administrative applications.



A central database server Sun S-790 will be installed for the management of the distributed database Oracle. The patient file hierarchy is vertically organized (patient identifiers --> list of examinations --> set of images, text and vocal comment per examination) and the selection is made with pull-down menus.

4.3. Image Processing and Compression

The necessary image processings for the diagnostic workstations have been presented in paragraph 4.1. Because the user is a physycian and not a specialist in image processing, the set of tools must contain only the indispensible ones which have to be defined with the radiologist. For the same reason, the processing interfaces has to be very simple and friendly with a reduced number of parameters to set up. Dedicated hardware (4) will be developed to allow real-time processing

Because large amounts of data are handled in PACS, compression techniques have to be implemented (4, 5). This task has to be transparent to the user. Dedicated compression is realized depending on the modality used and the textural characteristics of the image. Within an image, segmentation algorithms are used to discriminate different regions needing different compression algorithms and rates: the background with little information and the anatomic region which can be subdivided into the primary region (where the pathology is localized for example) and the secondary region. A ROC study will be implemented to complete this work. The different algorithms tested are the Discrete Cosine Transform, the Adaptative Discrete Cosine Transform, The Adaptative Block Truncation Coding, the Huffman Coding, the Run Length Coding... . The researchs developed by some members of our group in this area are presented in a more detailed way in a paper submitted at this meeting (6).

4.4. Radiology Information System

A feasibility study has been started to develop a RIS based on the 4ème Dimension database software which allows to create very friendly user interfaces and is open to other databases like Oracle... . This work should point out the specifications of the RIS in order to integrate this system to the PACS. Of particular interest is the planning of patients appointment to prepare data on the workstations and permit a rapid access to previous examination results. The connection between the IBM AS/400 and a Mac II has to be tested to permit reciprocal updating of the HPMS files and the 4ème Dimension files.

4.5. PACS Training Program

In order to facilitate the acceptance of the PACS among the future users at the CHL and to create a PACS knowledge in Luxembourg, a continuous training program will be realized. By involving the CHL community as much as possible in the developments, this goal should be reached and an optimal use of the system realized. Technical training for the maintenance of the system by the technical team will also be provided. A well-structured documentation work on the developments performed has to be continuously written and approved by the management committee for this program to be efficient.

4.6. Standards

As we already pointed out, standards have to be adopted at every level of our work to end up with an open system and remain

vendor-independent if possible. The choice of FDDI, Ethernet for networking, NFS, TCP/IP for transfer protocol, X-Window for interfacing and running distributed applications, Unix for the operating system, ACR-NEMA for image format, ISO/CCITT recommendations for image compression, VME Bus for implementation of dedicated hardware for the stations... has been made according to this requirement and allow the transportability of the different applications developed.

5. Conclusion

An overview of the state of the art of the PACS project at the Centre Hospitalier de Luxembourg has been presented in this paper. Developments are going on and some of our concepts have already been brought to concrete realizations in the field of image compression and workstation interface. The compliance to the medical requirements, the use of standards and the realization of friendly user oriented interfaces are our main concerns.

Although technological problems will probably occur in the future, we know from our short experience that human factors can interact and have to be considered. A step by step progression with well-defined phases is necessary to bring successfully the PACS technology into the medical world.

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PACS Technical Networking Design

Clinical and Research Radiology Network at the University of Florida

J.C. Honeyman, T. Gillespy, III, M. Frost, et al

Department of Radiology, University of Florida,
Gainesville, FL

Individual components of Picture and Archival Communications Systems (PACS) are under active development by a number of manufacturers. Unfortunately, there are no comprehensive systems available with the flexibility required to build a customized configuration for a specific Department or environment. The Department of Radiology at the University of Florida has taken a step-wise approach to connecting the research imaging and computer systems, clinical imaging systems, administrative and personal computers, and an imaging archival system in our Department. The immediate goal for each component of the system is to solve a specific problem or meet a need for the Department. However, the eventual goal is the integration of all radiologic imaging modalities.

Working Environment and Needs Assessment

The two teaching hospitals associated with the University of Florida, Shands Hospital and the Gainesville Veteran's Administration Medical Center (VAMC), are located within 400 meters of each other and are connected by an underground tunnel. A Magnatom 63 1.5 T MRI unit (Siemens Medical Systems, Islin, NJ), owned by the VAMC, is located in a separate facility adjacent to the VAMC. This facility also contains a Radiology research laboratory containing a 2.0 T imaging and spectroscopy research system (CISCO, Fremont, CA). A Signa 1.5 T MRI (General Electric, Milwaukee, WI), owned by Shands, is located in a different remote facility approximately 900 meters from Shands. The Nuclear Medicine division of the Department operates two single photon emission computed tomography (SPECT) imagers: a TRIAD (Trionix Research Laboratory, Twinsburg, OH) (jointly owned by the two hospitals) located in the VAMC, and a BIAD (Trionix) in the Radiology Department at Shands. In addition, an image processing research laboratory (IPL) is located in Shands that contains several general purpose workstations. The two radiology research laboratories (at the VAMC and at Shands) are equipped with a total of five Sun workstations. The Radiology Department also owns a separate dedicated image processing and display workstation, the DMI 3200 (Dimensional Medicine, Inc, Minnetonka, MN). The DMI 3200 is used for multiplanar and three dimensional image processing of images from the Signa MRI and two GE 9800 CT scanners (General Electric). The original needs assessment identified seven areas with either immediate problems or requirements for

increased productivity that suggested a network and/or PACS solution (see Table 1). The remainder of this section describes these areas.

- | | |
|---|--|
| 1 | Access to Signa images in Shands Radiology |
| 2 | Access to BIAD and TRIAD images and patient data in Shands Radiology |
| 3 | Archival of MR and CT images |
| 4 | Access to images and spectroscopy data by both research labs |
| 5 | Microcomputer communications |
| 6 | ICU access to portable radiographs |
| 7 | Access to DMI images by both research labs |

Table 1. Seven functional requirements for Radiology Network

Radiologists at Shands need access to images generated outside of the main Department, especially images from the Signa MRI and the two SPECT imagers. Due to the general clinical and research interest in CT and MR exams, studies are frequently removed from the Department film library and are not returned. Therefore, archival storage of these studies was identified as an urgent problem. In addition, the two research laboratories require access to images and spectroscopic data from remote sites.

In addition, Nuclear Medicine needs clinical access to the TRIAD and BIAD images with viewing and analysis capabilities on a radiologist's workstation. Reconstruction of SPECT images, initial analysis, and filming was usually performed on a remote disk-less workstation, with further analysis and research performed on the radiologist's workstation.

All radiologists, scientists, and secretaries in the Department have either an MS-DOS or a Macintosh computer in their offices for producing research papers, proposals, and correspondence. Cooperative research requires rapid interpersonal communication and the ability to easily transmit documents and data to others in the Department. With the faculty and staff widely dispersed, communication among the groups was identified as a problem area. In addition, radiologists also need to be able to input radiologic images on their microcomputers for incorporation into teaching and presentation materials.

Approximately 50,000 portable radiographs are produced per year in the five intensive care units (ICUs) at Shands Hospital. Unfortunately, clinicians do not have timely access to radiographs obtained in acute care situations since none of the ICUs are close the Department. Not surprisingly, these radiographs were frequently removed from the Department without proper signout and were subsequently lost without an official interpretation.

Imaging Network Design

RADNET is comprised of a fiber-optic cable ring with clusters of individual nodes connected via thinnet coaxial cable (figure 1). The thinnet coaxial cable runs ethernet and TCP/IP protocols, while a proprietary ring protocol runs on the fiber-optic cable. The connection between the thinnet and fiber-optic cable is made through WhisperLAN gateways (FiberCom, Inc, Roanoke, VA), with a repeater at each gateway and an extra repeater at the center of the installation. Currently, no subnets have been established. RADNET allows the two research laboratories to access images from the Signa and Magnatom MRIs, the DMI 3200 workstation and the SPECT imagers. Images from the 9800 CT scanners and other devices can be loaded into the DMI 3200 from magnetic tape and then made available to the network. The Nuclear Medicine component of the network allows patient lists and images from both imagers to be displayed on the TRIAD, the BIAD, an analysis workstation, and a radiologist's workstation.

RADNET operates at a theoretical rate of 10 Mbps. Typical transfer rates during average loading of the network are in the range of 1.5 - 2 Mbps. Performance of RADNET is adequate when the only active nodes are in Nuclear Medicine. When image data is transferred to or from either research laboratory while Nuclear Medicine is active, performance is significantly degraded.

Microcomputer Network Design

The Department personal computers are interconnected via an AppleTalk network. The AppleTalk network is comprised of a PhoneNET StarController (Farallon Computing, Berkeley, CA) connected to each computer through unshielded twisted pair cabling. TOPS network software (Sun Microsystems, Alameda, CA) on the personal computers and one of the Sun computers in the IPL allows printer sharing, print spooling, file transfer among all three computer types, and the ability to mount and publish volumes for sharing hard disk resources. Electronic mail is performed by InBox (Sun Microsystems), which has versions for both the MS-DOS and Macintosh computers. A FastPath 4 gateway (Kinetics/Excelan, Walnut Creek, CA) connects the AppleTalk and ethernet portions of the network.

The AppleTalk network operates at 230.4 kbps. Performance has been adequate to date with 10 Macintosh, 22 MS-DOS and 1 LaserWriter Plus active nodes.

ICU Teleradiology

Portable images are transferred to the ICUs by a dedicated teleradiology system, the Clinical Review System (CRS) (Dupont Medical Division, Wilmington, DE). The CRS is composed of a laser digitizer and server module in the Department which digitizes the portable radiographs. The server transmits the digitized images to one of 5 display stations in the ICUs over thicknet coaxial cable using a modified ethernet protocol. An

additional display station is located in the image processing laboratory. Each display station has a 160 Mbyte hard disc capable of storing 120 radiographs digitized at 1024 x 842 x 12 bits resolution. The CRS is not presently connected to RADNET.

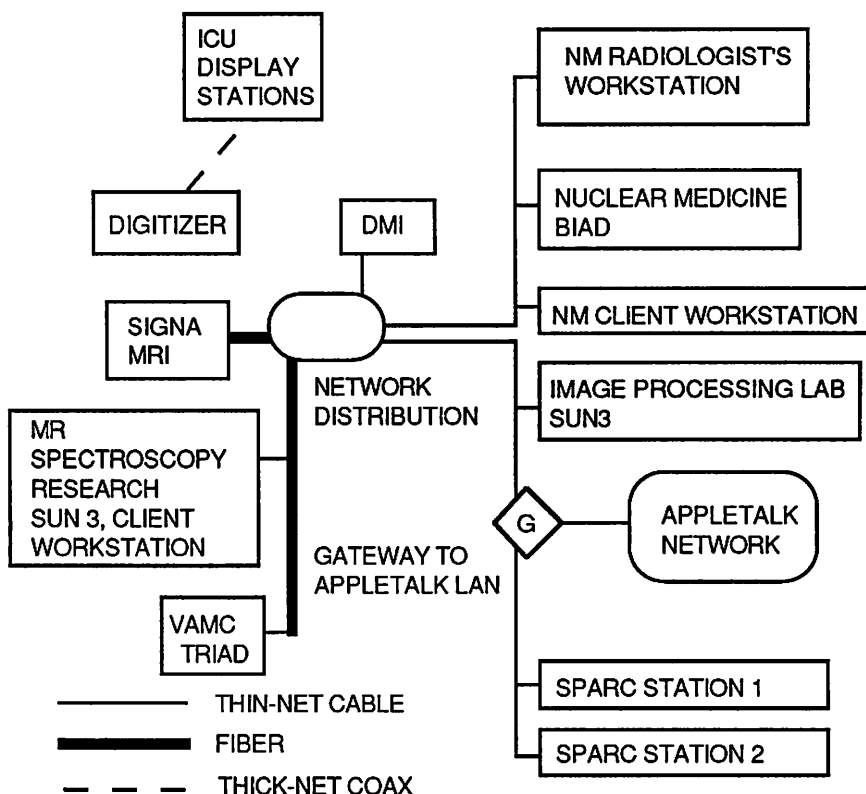


Figure 1: Initial Network Configuration

Future expansion

The original network and teleradiology systems meets all our requirements except the archival of MR and CT images. Expansion of RADNET is planned to allow direct digital acquisition of conventional radiographs, archival of images from all modalities, and advanced display and analysis capabilities. In addition, the teleradiology functions will be incorporated into RADNET.

Our design activities include identification of locations of work areas for radiographic interpretation and consultation, the location of bridges to create

subnets for traffic load containment, the solution to problems of file and protocol conversions for equipment integration, and identification or development of display devices to meet the varied needs of end users. The Department is separated into logical, physical and functional clusters (table 2). The logical clusters generally define divisions or subspecialties in the department and are used to identify locations of display and analysis workstations for interpretation and consultation. Physical clusters describe the equipment in terms of location for the identification of possible subnets to reduce overall network traffic. Functional clusters define groups of similar image modalities and are used to specify unique display, storage, and analysis requirements.

Clusters	Examples of Clusters
Logical	Neuroradiology Abdominal Imaging Musculoskeletal Radiology
Physical	Locations of Equipment
Functional	MRI CT Ultrasound Nuclear Medicine Radiographs

Table 2. Examples of Design Clusters in Radiology

Neuroradiology has been identified as having the highest priority for archival of MRI and CT images. We have chosen a Medical Imaging Gateway (Vortech Data, Inc., Richardson, Tx) as the center of a communication management, archival database, and image display system. Long term archival will be through the Vortech IARS Image Archival Retrieval System with dual 4.0 Gbyte Optimum optical disk drives, a 131 platter optical jukebox, and 2.0 Gbyte magnetic working disk. The system will initially archive neuroradiology images from the Signa and two 9800 CT scanners. The medical imaging gateway will interface with the DMI 3200 and the research laboratories through the existing RADNET, and with two dual monitor Imlogix 1000 Display Stations through a Fiber Distributed Data Interface (FDDI) protocol. The network has been expanded to include bridges internal to RADNET and a router for connection to Medical Center

and University networks. The new network configuration is based on the original network with additional components (figure 2).

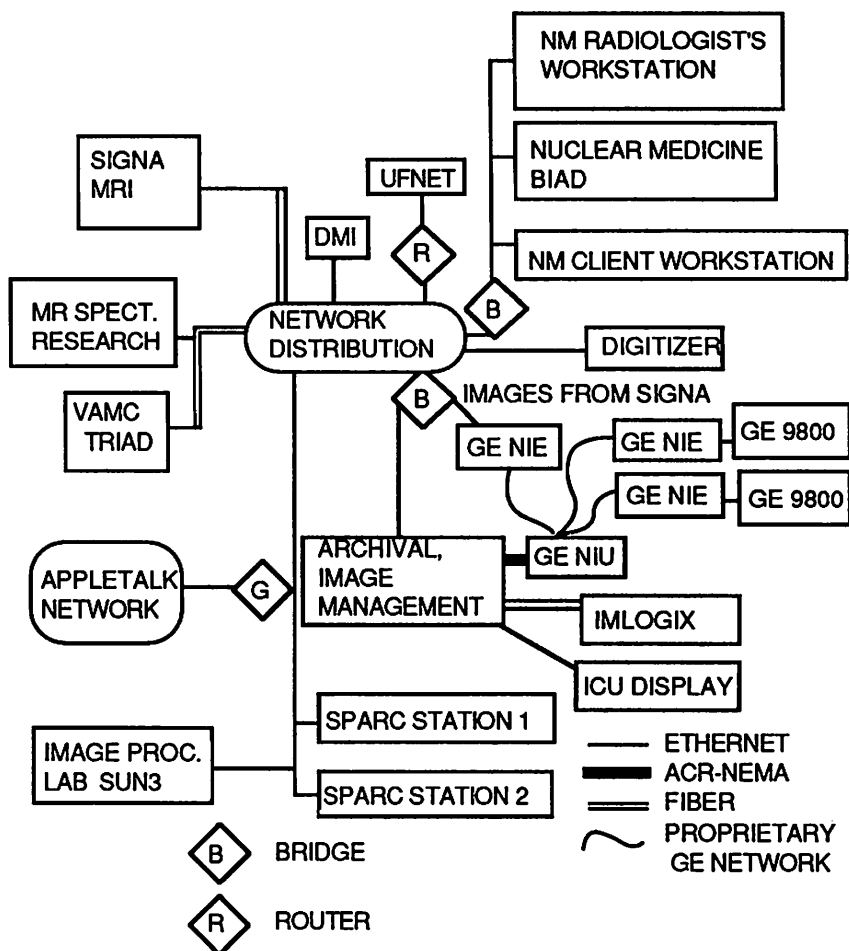


Figure 2: Updated Network Configuration

Summary

Initial evaluations of RADNET, teleradiology and the AppleTalk network indicate that clinical radiology networks are feasible and can result in increased productivity, improved patient care, and potential cost reductions through resource sharing. Our design experience has demonstrated the importance of a correct initial network configuration with planned expansion capability.

Hospital Integrated Picture Archiving and Communication (HIPACS): A European Project

R. Mattheus, F. Moyson, Y. Temmerman, et al

Department of Radiology, University of Brussels,
Brussels, BELGIUM

In recent years, the field of medical imaging has gradually shifted towards digital techniques. The management of the large amount of medical images and information generated by today's clinical services is a growing problem. For the management of this enormous amount of images a PACS environment can be set up. But technical, economical and organisational problems have limited the exploitation in daily clinical routine work. The main goal of the HIPACS project is preforming a platform for a second generation PACS concept. The second generation PACS concept will be a multi-vendor environment integrated in the hospital. A phase upgradeable approach will be chosen so that a stepwise introduction can take place; this is also more realistic from an economical and organizational point of view. Universities, industry and hospitals of Europe are working together to perform this task. The paper will give a brief overview of the project with a focus on networking at the university Hospital of Brussels (VUB).

1. INTRODUCTION.

1.1. HIPACS.

In June 1989, HIPACS became an official CEC (Commission of the European Communities) sponsored project, with as its Prime Contractor the PRIMIS Research Centre. Michel Osteaux became project leader, Rudy Mattheus project manager.

Ten partners from five European countries joined forces in this project and brought together complementary skills in medicine and information technology (IT). Their origins lie in the industry (Philips Hamburg; BAZIS Leiden), in hospitals (Klinik für Radiologische Diagnostik Aachen - Univeristy Hospital VUB Brussels) and in universities (University of Ulster - Institute for computer Science Crete- Lehrstuhl für Messtechnik RWTH Aachen - PRIMIS Vrije Universiteit Brussels). PRIMIS has two subcontractors, BARCO and GE-CGR.

The aim of this project is the identification and, whenever possible, the elimination of bottlenecks that hamper the implementation of a full-scale Hospital Integrated PACS. In order to achieve this goal, coordinated research efforts in the field of digital network design, data management, and diagnostic imaging workstations are required.

1.2. HIPACS project topics.

The modelling and the related coupling of PACS and HIS

When introducing an image management level, an important point in using the PACS in clinical routine is its integration with the patient management system of the hospital, the Hospital Information System (HIS) and Radiology Information System (RIS). Patient information must be shared between these three levels.

A prototype of a high-speed network for image transfer .

For transporting this enormous amount of information classical networking is not adequate. To solve this problem work is being done in the direction of optical networking. Fast image communication techniques are being studied, developed and evaluated.

A model of a heterogeneous network structure will be used to study routing optimization of image and other data in existing and future networks.

Knowledge based network management techniques are being developed, so that it will be possible to route these images to places where they are normally needed. These techniques are based on the organisation and medical information of the Radiology department. The development of these tools started two years ago in our department.

Multimedia data-base software with facilities for intelligent information retrieval

Images, patient data, electrocardiograms, ..., all these multimedia data must be considered for storage and retrieval. Retrieval mechanisms based on the information contained in the images are also an important topic.

An adaptive user-interface for increased diagnostic efficiency of existing image workstations.

Medical knowledge is not only important for network management; it is also useful information for defining the required behaviour of the user-interface. Suggestions will be made as to which images should be displayed where on the reporting stations.

2. DISTRIBUTED NETWORKING.

2.1. Introduction.

One can choose very fast networks in order to try to solve the image communication problem. In the AZ-VUB Ethernet was chosen for communication.

This requires the setting up of a network topology and management, which can render the whole system more acceptable for the radiologist and which allows for better work than the currently used manual method. Using this, the intention is to build a distributed PACS archiving system, which has a management system based on an expert system. The concept is that images, of which the radiologist foresees that he will need them the next day (e.g. images of patients having an appointment for that day) are fetched from the archives the night before and are stored in the radiology department's own local memory, so that the radiologist can consult 90% of his images as it were instantaneously. Only the images of which he had not foreseen that he would have to use them, will have to be waited for, but if these had to be sought manually, he would probably have to wait for a considerably longer time.

2.2. Phased build-up.

The AZ-VUB project is executed in distributed upgradeable phases. In a first phase, PACS systems are set up at image capture on a limited scale: a local network with acquisition, display and storage, and this for each type of image generating equipment. The CT-PACS consisting of 2 CT units (Siemens) a prototype 3 screen reporting station (Siemens), local storage and archiving possibilities. A hardcopy unit (3M) used for the 2 CT's and reporting console. The MR-PACS section consists of 1 MR (Siemens) and a powerful image-processing station and local storage and archiving possibilities. At the emergency department the PACS section consists of a laser-digitizer, a 2-screen reporting console and a prototype DR (II) (CGR-GE). In the middle of 1990 a test at the orthopedics department with an Imlogix viewing station will be set up. Also a project with 3M has been set up to manage ultrasound images. Together with Barco, a local PACS environment was built for the management at the intensive care unit of images generated at the bedside.

These subsystems are linked via Ethernet to a backbone network in the radiology department. This backbone network consists of a buffer storage, optical disks, a PACS reporting console and a hardcopy unit (3M). The network currently in use (MR, CT and radiology) has a length of 300 metres.

At the moment, an optical fibre network with a length of 1,5 km is being completed. This network consisting of some 20 parallel fibres will not only be used for PACS, but also for a number of other hospital informatics projects. It will allow for further extension of the PACS system towards the nursing units. Experiments are also being considered which will extend outside the hospital walls (e.g. towards a radiologist on duty, who can then, during the week-ends, give advice, based on images sent to his home, to less experienced radiologists inside the hospital).

2.3. Network control.

Control over a network can be centralized or distributed. Centralized control means that one of the devices on the network has absolute control over who can use the network at what time.

In a network with distributed control, none of the system nodes has explicit control over the network. Instead, control is distributed evenly among all members in the network. The merits of distributed systems include greater reliability, simpler bus structure, and more flexibility on system configuration than the centralized systems. However, they introduce larger overheads and therefore reduce the effective channel bandwidth. Nevertheless, the distributed systems are still the most popular for currently implemented PACS.

ETHERNET is a typical example of a distributed control network. Each node is attached to a single high-speed coaxial bus by a connector clamp, a transceiver and a controller. The transmission medium may be occupied by only one system component at any one time instant. As a result each node has to compete for use of the common bus under a decentralized control strategy known as carrier sense multiple access (CSMA). Under this scheme each node listens to the carrier before it attempts to transmit data. If there is no carrier already on the bus (idle), it transmits its data. Otherwise, it waits for a random period of time before its next attempt.

ETHERNET uses coaxial cable as a transmission medium. Its theoretical transmission speed is rated at about 10 megabits per second. However, because of overhead in the system, the effective transmission rate is only about 1 megabits per second.

3. NETWORK TOPOLOGIES FOR PACS.

It is possible to define 4 main PACS topologies: closed line, central line, distributed network and distributed subnetwork.

3.1. Closed line.

A closed line is modality-dependent and only aimed at connecting devices of the same modality (CT, MR,...) together, possibly, with a second console. A typical construction will contain two modalities of the same type connected with an image console.

3.2. Central line.

Added to the first topology is a central computer system with a local store, data base, archiving possibilities and display and research software for the reporting node. It is possible to interconnect devices of different modalities.

3.3. Distributed network.

Added to the previous topology is the possibility to make use of distributed processing on the different computers in the network.

3.4. Distributed subnetworks.

Each sub-department (MR Department, CT Department, Emergency Department,...) has its own small PACS environment with local store, reporting consoles, hardcopy units and a gateway or bridge to the PACS-backbone network which interconnects all the sub-networks. This approach allows distributing the image-flow over the network, making traffic on a single subnetwork possible without interfering with the traffic on the other subnetworks. Figure 1 gives an example of this kind of network.

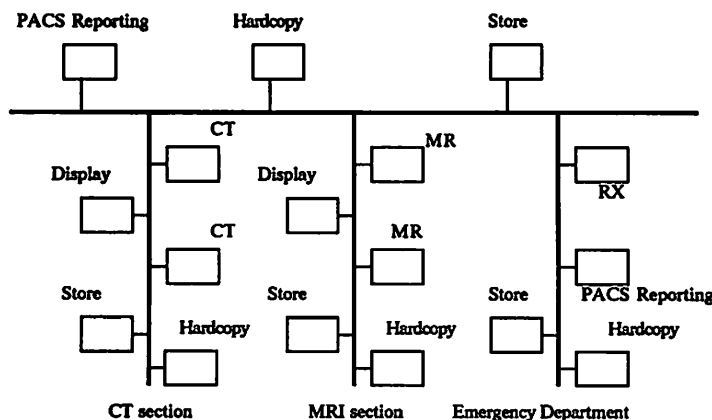


Figure 1
An example of a distributed PACS subnetwork.
The three departments on the figure are interconnected
through the PACS-backbone.

4. THE NETWORK MANAGER.

4.1. Introduction.

The network manager shell insures that traffic on the network is optimal. Buffering, decentralization and pre-fetching are techniques used to allow faster access of examinations (possible delays are due to image transport).

During the night, a link between the Radiology Information System (RIS) and PACS allows the search in the archives of all images of patients scheduled for control or new examinations the following day. This procedure is called prefetching.

All network management techniques have been developed in-house. A program database is used to maintain, change and further develop these programs. This is essential because of the fact that a lot of people are involved in the project.

PACS has a hierarchical architecture introducing several levels for image transport, control, security and management. The system is distributed according to the image, data, hardcopy and control level.

Terminals are integrated on the different acquisition modalities containing the control functions to request image transfer. On each modality the radiologist can select different functions: archive, report, special study and temporary storage. The messages on the control layer are stored on queues managed with different priorities. The image-manipulation and reporting console communicates on image-transfer, control and security level. The communication with the optical disk-image data-base takes place via message structure, in time-sharing mode on the control level and by batch processes created by the control layer on image-transfer level (making use of statistical information). Images are converted to the SPI (ACR-NEMA) format. The network management and security-level is centralized. Any existing data-base system may be used to link images to non-image information. The Standard Product Interconnect (SPI) standard (an ACR-NEMA superset) is used for image format and network commands.

The management level performs the logical management of the stored images and takes care of all supervisory and administrative tasks. In addition it performs the logical link of image to related non-image information such as patient data. The security level forms the top layer, which supervises the different tasks, notes the history of events and controls login and password information.

This hierarchical structure of the network allows the workload of the network to be optimized and enables us to handle image transport 24 hours a day.

The network shell uses different input parameters, correlations between the workload, report and image generating functions at the radiology and emergency departments (amount of images per hour or day). By processing this information and other statistical data (appointments, priorities,...) we have a constant continuous throughput function instead of a highly variable discontinuous function, and are able to use our PACS environment in clinical practice.

4.2. Simulation of the network.

A prototype of a network management system has been implemented (Figure 2). Its different components are a network model, a simulator, traffic and flow managers and configuration and strategy managers. The physical link between this simulation and the actual PACS network has not been realized yet, but it is our aim to use the different managers to optimize the actual network in real-life situations.

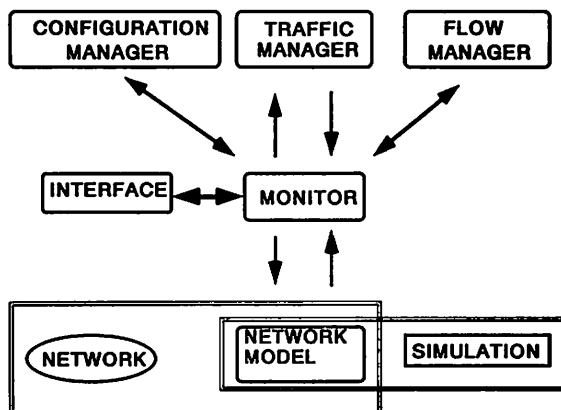


Figure 2

An overview of the Network Management Simulation System.

A graphical editor allows the interactive specification of a specific network configuration, i.e. a composition of network segments with associated image acquisition stations, viewing stations, storages, hardcopy facilities, etc. The combination of the generated network model and the simulator allows us to test and experiment with different traffic management strategies and different network configurations.

Two main modules of the network management system implement the traffic management task. Briefly, the flow manager creates and alters image transfers, while the traffic manager sequentialises those image transfers over the network.

A fundamental requirement is to make the traffic management strategy and the domain knowledge used in it, explicit. To fulfil this objective, both the flow manager and the traffic manager make extensive use of strategy-rules, which are the explicit representation of bits and pieces of common sense and/or domain knowledge related to managing the PACS network.

4.3. Traffic manager.

The function of the traffic manager is to sequentialise the image transfers over the network according to a selected traffic strategy. The implementation of this module is distributed, i.e. on each segment of the network a single traffic manager is assumed.

A hierarchy is defined among segments. Each segment is connected to its only supersegment by means of a bridge. The highest segment in the hierarchy, i.e. the segment which has no supersegment, is called the backbone of the network. In accordance with this, the traffic manager of a segment's supersegment is referred to as the supervisor of this segment.

Traffic managers receive transfer requests, i.e. requests from image stations to transfer an image, originating from stations located at the traffic managers' segments. More details of such requests (e.g. the source, destination and priority) were filled in by the flow manager.

These completed transfer requests, also called transfers, are stored on transfer queues. All logic storage units such as image stations (logic storage units will be explained later on) and traffic managers have transfer queues. A queue of a traffic manager is called the queue to its supervisor. The decision on which queue to store a transfer is made according to the queueing strategy of the traffic managers.

For each image transfer one traffic manager, the so called master of the transfer, is responsible for activating the transfer. The master of a transfer is also set according to the traffic manager's queueing strategy.

A traffic manager 'manages' the queues of modalities on its segment and the queues of traffic managers on its subsegments (i.e. the segments lower in the hierarchy which are connected to this segment with a bridge), i.e. it is responsible for serving the transfers of these queues in a correct order. The queueing strategy of traffic managers defines the way in which a transfer is put on a queue which is managed by the transfer's master.

Traffic managers constantly investigate whether transfers waiting on the queues which they have to manage are allowed to be executed and consequently interrupt other running transfers. The traffic managers' interrupt strategies define different solutions (mostly based on the urgency of different transfers) to deal with this task in a satisfactory way.

4.4. Flow manager.

The flow manager is responsible for many tasks. One of the tasks of the flow manager is to decide where an examination must be stored at each time and to distribute images over the network's storages to minimize network traffic for later retrievals of the examination. The flow manager also has to ensure that urgent transfers are served sooner than less urgent transfers, and that reasonable response times are achieved for all transfer requests.

Further tasks of the flow manager are organising prefetches at non-peak hours to minimise network load at peak hours and monitoring the load factor of the storage media on the system to prevent overflow. Just like the traffic manager, the implementation of the flow manager is distributed, i.e. on each segment of the network a single flow manager is assumed.

Flow managers receive transfer requests from stations located at the flow managers' segment. In turn, they send completed transfer requests, i.e. transfers, to the traffic manager of their segment. Different types of transfers are defined. A transfer request originating from an acquisition station will result in an acquisition transfer, one originating from a consultation station will result in a consultation transfer and one from a reporting station in a reporting transfer. Other existing transfer types are copy transfers and copy-before-delete transfers, which copy or move examinations to other storage devices.

Flow managers assign a priority level to a transfer. Knowledge about types of transfers, their importance, their frequencies, etc., is necessary to make such a decision. Some very important transfers receive the status of emergency transfers. Priorities and the status of emergency transfers are assigned to transfers to make it possible for the traffic manager to differentiate between urgent and less urgent transfers.

To decide where an examination must be stored at each time in order to minimize network traffic for later retrievals of the examination, the flow manager needs knowledge about patient-flow and examination-flow. Supported by this knowledge, a flow manager assigns a source and destination to a transfer. Examinations can be sent to or taken from logic storage units. These are logical storage devices which group sets of physical storage devices (i.e. disks) which all store examinations according to a common purpose. Logical storage units are the image stations

(acquisition, consultation and reporting stations), the local stores, local archives, central stores and the central archive. Local stores group devices which have as main purpose to store the acquisitions made by acquisition stations on each segment. Local archives archive examinations which are expected to be needed in the near future by modules on each segment. Central stores store examinations which are unlikely to be needed in the near future and the central archive archives examinations which are of no interest in the near future (e.g. after a period of 6 months an examination can be stored in the central archive).

To distribute images over the network's storages to minimize network traffic for later retrievals of the examination, copy transfers are created by the flow managers. To ensure that reasonable response times are achieved for all transfer requests, flow managers adjust the priority value and emergency status of waiting transfers. Also adjustment of source and destination of transfers is a task of the flow managers.

Monitoring the load factor of the storage media on the system to prevent memory overflow can be done in different ways, as will be described in the next chapter. Organising prefetches at non-peak hours to minimise network load at peak hours needs the hospital appointment system and common sense. At this moment, prefetching is done manually in the prototype.

4.5. PACS strategies.

Strategy-rules are the explicit representation of bits and pieces of common sense and/or domain knowledge related to managing the PACS network. Strategy-rules are grouped in rule-classes which correspond to a strategy for handling a specific subtask of the management task. Often alternative ways for handling the same management task are available. The corresponding rule-classes are in turn grouped for classification purposes.

Two modules make extensive use of strategy-rules, i.e. the flow-manager and the traffic-manager. Selecting within each of these modules a strategy for each of the subtasks involved results in the specification of a particular flow-strategy and traffic-strategy respectively. A traffic-strategy and a flow-strategy together specify the overall strategy of the network manager. Strategies interact, they can not be combined arbitrarily.

The strategy manager is there to evaluate the performance of the network and to advise on possible improvements of the strategy employed. It does this by analysing the logs generated by the simulator. It contains expert knowledge on how certain types of problems can be avoided. The proposed changes can then be evaluated by editing the traffic and flow manager module, running the simulator and again analysing the resulting logs.

The configuration manager evaluates the performance of the network and advises on possible improvements of topology and configuration. Just like the strategy manager, this module analyses the logs generated by the simulator. It also contains expert knowledge and its suggestions are also checked by running a new simulation with the necessary changes.

5. CONCLUSION.

Modular network architectures, capable of reacting to growth and changes in traffic patterns are essential. Partitioning the network into patterns is essential as well. Partitioning the network into subnets will reduce bandwidth requirements and increase response time by distributing network traffic. A hierarchical decomposition will make it easier to use transmission techniques with an optimum choice on each level. As an additional benefit, this design strategy offers the possibility to start introduction of PACS into a given environment by establishing the local sub-system first. In subsequent steps, the integration of a complete PACS could be performed, accompanied by a step-by-step training of personnel and a gradual change of work routines. In the future new techniques for faster communication will be available, but there will probably always be an advantage in management of image distribution in a clinical environment.

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The ACR – NEMA Standards: A Tutorial on Their Structure & Use

Steven C. Horii

Department of Radiology, Georgetown University Hospital
Washington, DC

ABSTRACT

The ACR-NEMA Standard was developed initially as an interface standard for the interconnection of two pieces of imaging equipment. Essentially, the Standard defines a point-to-point, hardware connection with the necessary protocol and data structure so that two differing devices which meet the specification will be able to communicate with each other.

The Standard does not define a particular PACS architecture, nor does it specify a database structure. In part, these are the reasons why implementers have had difficulty in using the Standard in a full PACS.

Recent activity of the Working Groups formed by the Committee overseeing work on the ACR-NEMA Standard has changed some of the "flavor" of the Standard. It was realized that connection of PACS with hospital and radiology information systems (HIS and RIS) is necessary if a PACS is ever to be successful. The idea of interconnecting heterogeneous computer systems has pushed Standards development beyond the scope of the original work. Teleradiology, which inherently involves wide-area networking, may be a direct beneficiary of the new directions taken by the Standards Working Groups.

This paper will present a brief overview and history of the "parent" standard, describe the structure of this standard, and discuss the "offspring" of the standard with regard to the activity of the Working Groups.

INTRODUCTION

Though the concept of PACS has been well embraced by the medical imaging community, this has been so largely on a small-scale basis despite the fact that satisfactory technology for implementation has been available for several years. Though perhaps the major reason for this slow adaptation is the cost of systems, the

inability to connect multiple-vendor imaging departments to networks (or network interface units, NIUs) is also a contributing factor.

This problem, the lack of hardware and software standards for image interchange, prompted the formation of the ACR-NEMA Digital Imaging and Communications Standards Committee. The original goal of the Committee was to produce a standard which would allow imaging equipment from different manufacturers to exchange images and associated data.

HISTORY

At the first U.S. PACS meeting, held in 1982 in Kansas City, acquiring image and image descriptive data from different manufacturers' equipment was already seen to be a problem.¹ Most groups doing PACS-related work were acquiring images for their systems either through digitized video (which suffers from limited dynamic range) or magnetic tape. The latter method meant understanding the tape format and pixel packing technique, something the manufacturers were not always willing to reveal. The potential users of PACS, the radiology community, asked the American College of Radiology to help find a solution to this problem. Engineers who worked for the manufacturers also began to realize that there was little to be gained by keeping image formats proprietary. The manufacturers were represented in issues of standardization by a number of groups, but their Association, the National Electrical Manufacturers Association (NEMA) had experience in standards related to medical imaging equipment. The two organizations first held exploratory talks in late 1982, and the result was the formation of the ACR-NEMA Digital Imaging and Communications Standards Committee in early 1983.

The original charter of the Committee was to develop an interface for the exchange of image and related information between a piece of medical imaging equipment and whatever was on the other side of the interface². In defining this as its charter, the Committee restricted its range of activity. The resulting standard would not be a standard for a full PACS, a database, or a network. However, the ability to bring digital image information out of a piece of equipment over standard hardware using a standard format was felt to be a goal worth pursuing.

The Committee formed three Working Groups, each addressing a particular aspect of standardization. The Working Groups were assigned to hardware and protocols (WG I), data format (WG II), and system and performance specifications (WG III). Coordination of the Working Groups was assured by both Committee action and the participation of members in more than one group.

The Working Groups began their tasks by examining existing standards since it was the intent to use other standards if possible. Hardware standards examined included IEEE 488, Ethernet, Intelligent Peripheral Interface (IPI), SCSI, DEC®

DR11W, DEC Unibus®, and Multibus. Data formats of AAPM Magnetic Tape, LANDSAT, NATO magnetic tape, and the Japanese JAMIT were examined for possible useful data structures. While some ideas were drawn from these standards, none in particular was satisfactory for all the requirements defined. In addition, because of antitrust regulations in the United States, NEMA must operate under certain constraints. This prohibited the use of certain proprietary interfaces, or interfaces which would unfairly benefit a single manufacturer. The effort of examining standards did not end when the Working Groups concluded that a new specification would have to be written. The MAP/TOP standard, for example, was discussed even after the ACR-NEMA draft was written.

Because of rapidly evolving PACS research, it was thought necessary to get a standard written as quickly as possible. The Working Groups went through numbers of proposals by circulating them to each other and the engineering staffs at the parent companies. Within two years, a standard had evolved which was thought to meet all the requirements set forth by the Committee. Following Committee approval, the document was approved by vote of the member companies and ACR representatives. The approved draft was distributed at the Radiological Society of North America meeting in 1985 and published as a NEMA Standard (ACR-NEMA 300-1985) in the same year.³

ACR-NEMA 300-1985: THE PARENT STANDARD

This Standard, titled "Digital Imaging and Communications" includes the data format, protocol, and hardware interface necessary for transmission of data between two pieces of medical imaging equipment. The location of the interface plane is defined to be between the two devices as shown in Figure 1.

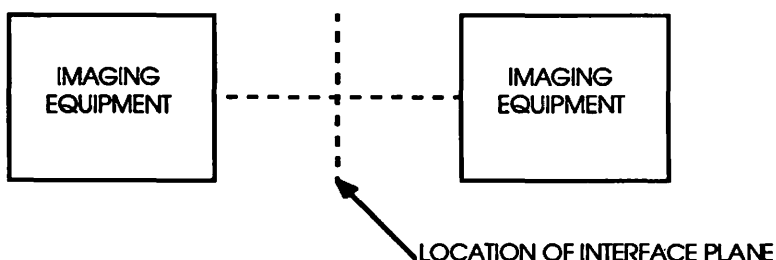


FIGURE 1: LOCATION OF THE ACR-NEMA INTERFACE PLANE

Though not intended as a network standard, it was certainly anticipated that for use in a PACS environment, connection to a network of some form would be essential. In this case, the device on one side of the interface would be a network

interface unit (NIU), the network in use then determining the nature of the NIU. It was recognized that such a unit would have to have significant local processing power, probably on the order of a microcomputer. However, given the magnitude of the interfacing problem, this was thought to be a reasonable approach. A diagram of how the ACR-NEMA interface might be used in a network environment is shown in Figure 2.

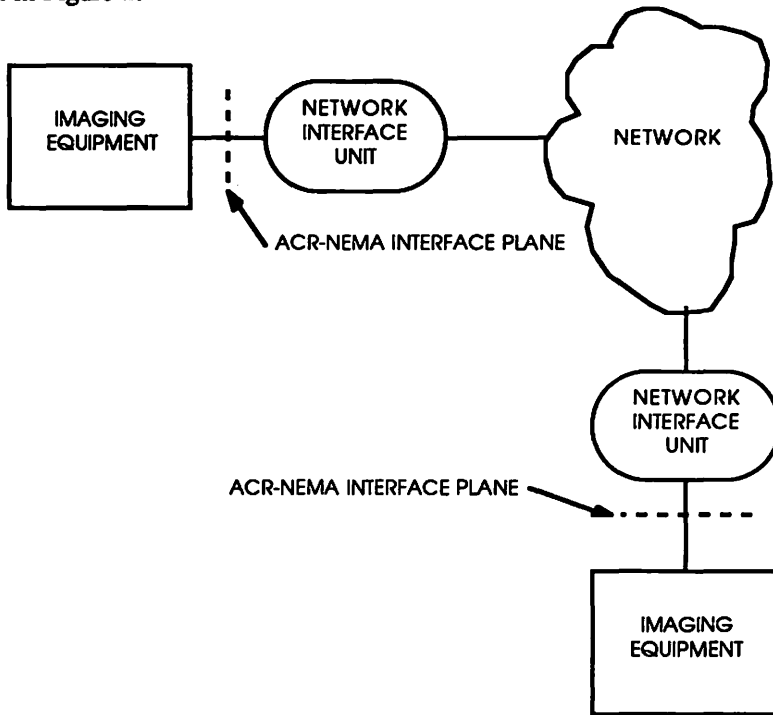


FIGURE 2: LOCATION OF ACR-NEMA INTERFACE PLANE WITH A NETWORK

In designing the interface, the Working Groups used the International Standards Organization Open Systems Interconnect (ISO-OSI) Reference Model.⁴ In this model, the functions of a network communications interconnection are split into well-defined layers. Each layer performs a specific set of operations, providing services to the layer above and below. On each side of an interface, the same layers are performing the same functions, so to the programmer, the layers can be thought of as communicating directly with their equivalents. This "peer-to-peer" communication actually occurs in a vertical direction in the layers, and the true connection is only at the physical layer.

The ACR-NEMA Standard builds upon the ISO-OSI Reference Model in that specific layer functions were defined. The ACR-NEMA document refers to named layers and divides functions accordingly. An attempt was made to adhere to the layer functionality of the ISO-OSI model, but the ACR-NEMA Standard is not ISO compatible. In addition to differences in definitions of layer-to-layer connections (called interfaces in ISO terminology), there is one convention used in the ACR-NEMA Standard which violates an ISO-OSI concept (this is discussed later). The correspondence between the ISO-OSI layers and ACR-NEMA layers is shown in Figure 3. The discussion that follows will start at the topmost (or Application) layer of the Standard and proceed downward to the physical layer.

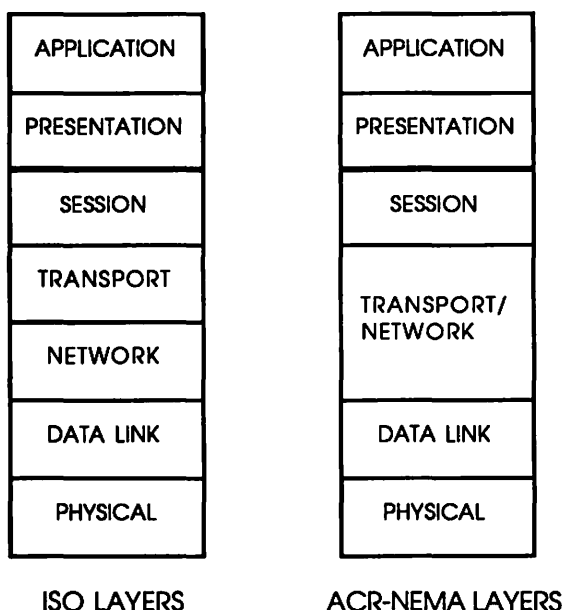


FIGURE 3: SIMILARITY OF ISO AND ACR-NEMA LAYERS

When medical imaging studies are performed on a patient, the demographic information about that patient, the data on how the images were acquired, and the images themselves form a set of data amenable to display and interpretation (a data set in ACR-NEMA terminology). In the Standard, this data set is further associated with commands, and the whole is called a message. The commands indicate certain fundamental operations on the data: SEND, GET, FIND, and MOVE. SEND is the basic command, allowing an imaging device to output its data. GET allows a requesting device to obtain a specific data set. FIND is a primitive search tool which will locate all data sets which match the information requested. MOVE allows one device to request a second to send data to a third. In the Standard,

assembly of the message from individual data items and commands, and formatting of the result of this assembly takes place in the Application and Presentation layers. The aforementioned problem with OSI compatibility results from the upper layers, which build the message from commands and the data set, making a distinction between data types. Commands and data travel in different types of packet, but this is not encoded until the lower layers. This means that the upper layers have to look into the packet to determine the type upon receiving a packet, or have to tell the lower layers whether what is being passed down is command or data. One of the areas of investigation by the Working Groups is how to either eliminate this problem, or work around it, while remaining compatible with existing implementations.

The message format itself consists of data elements collected into groups. Each data element (for example, patient name) consists of two numeric fields forming a key, equivalent to the name of the data element. This is followed by a length field and the element value. The key (which is fixed length) consists of the group number and element number (in hexadecimal). The length field is a 32 bit integer which gives the length of the value field in bytes. The value field is therefore of variable length, the only restriction being that lengths must be an even number of bytes (padded if necessary). Note that this 32 bit length allows for some very large elements. Though questions were initially raised about this size, recent work is proving its value. Figure 4 shows an example of the structure of an ACR-NEMA element.

Group	Element	Length	Value	Meaning
0008	0010	000C 0000	4341 2D52 454E 414D 3120 302E	'ACR-NEMA 1.0'

FIGURE 4: ACR-NEMA DATA ELEMENT STRUCTURE

Groups were defined in order to collect elements in a logical fashion. This was not entirely successful as it seemed some elements could be located in two places. Since elements are not duplicated (except with specific elements in group 0000 hex), this resulted in imperfect groupings. However, the group-element keys are unique. The structure also provides for expansion in that some "room" was reserved between assigned group and element numbers to allow for additions. To provide for user-defined or manufacturer specific data, a structure of shadow groups was defined. This also provided a mechanism by which new groups or elements could be used until considered for incorporation into revisions of the Standard. The defined groups of the Standard are given in Table 1.

Though it appears that the Standard contains a great many elements which need to be sent with each image, in fact, some elements are specific for certain types of images. For many medical images, the collection of elements will be a small fraction of the total message size. Also, the elements were assigned types based on

how important they are for interpretation. For example, pixel format information is essential whereas equipment manufacturer name is probably not. The former is considered a mandatory data item (a type 1) and the latter is optional (type 3). There are also type 2 elements which are considered mandatory, but which conceivably may not be known at the time of the examination. Unlike type 1 elements, which must be sent and must contain valid data, type 2 elements may be sent with a zero length, indicating that the value is not known. Defaults exist for many elements and fall into type 1D and 2D categories. The difference between these is that the default is always assumed if a type 1D element is not sent. It is not possible to send a zero length (indicating "unknown") for a type 1D element whereas this is possible for a 2D (in which case the default is not assumed). Type 3 data elements are those which are not essential for interpretation, but which may be important for certain medical images.

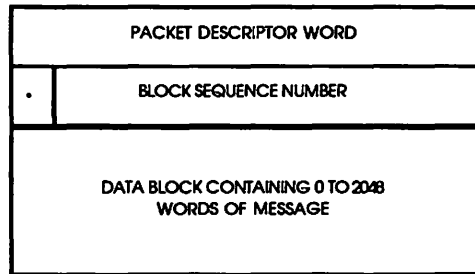
Table 1
ACR-NEMA Standard Groups

Group Number	Type of Information	Description of Group Contents
0000	Command	Information which provides for end-to-end communication capability between two pieces of equipment
0008	Identifying	Information which provides unique image identification parameters to the user
0010	Patient	Information related to the patient
0018	Acquisition	Information related to the image acquisition device and imaging procedure
0020	Relationship	Information relating the image to the location within the patient and to other associated images
0028	Image presentation	Information related to the parameters of image presentation
4000	Text	ASCII text
6000-601E	Overlay	Information related to overlay pixel data associated with an image
7FE0	Pixel data	Image pixel data

Once the message is assembled, it is sent down to the Session layer. The Standard has provided "hooks" in this layer for a multiple virtual channel protocol.

In effect, virtual channels allow the single physical connection to support multiple logical connections. Connection control words and message source and destination fields are defined in this layer for incorporation in layers below.

The Transport/Network layer takes the message with the information from the Session layer, and fragments the message into packets. Packets consist of a block of the message (0 to 2048 bytes) plus a packet descriptor word and block sequence number. The packet descriptor word contains the information on channel number as well as packet type (channel control) and packet service class (i.e., whether or not to acknowledge each packet). Packet structure is shown in Figure 5.



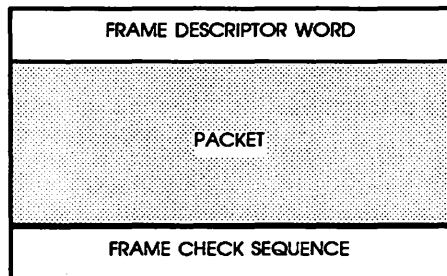
NOTE: WORDS ARE 16 BITS LONG

MOST SIGNIFICANT BYTE

* LAST BLOCK FLAG FIELD

FIGURE 5: ACR-NEMA PACKET STRUCTURE

The now packetized data proceeds down to the Data link layer. Each packet is enclosed by a frame descriptor word and frame check sequence to form a frame. The frame descriptor word consists of a frame type (e.g., data and status) and a parameter field (length or status depending on frame type). The frame check sequence is a checksum which allows for error detection. Figure 6 shows the structure of an ACR-NEMA frame.



NOTE: ALL WORDS ARE 16 BITS LONG

FIGURE 6: ACR-NEMA FRAME

Frames are sent to the Physical layer which handles transmission across the interface. The physical interface consists of 16 asynchronous parallel lines with control signals. The drivers for the signal lines are EIA RS485 standard, driving differential pairs for high noise immunity. The connector is a widely available 50-pin micro-type and must be female on the equipment. Since the interface is designed to operate in a master-to-master environment, the control lines cross over in the cable. With the specified drivers and a cable length of 15 meters, hardware speeds of 8 megabytes per second can be achieved. Since the interface is asynchronous, however, much slower rates (limited only by the 1 second idle timeout) are accommodated. Figures 7 and 8 show the signal lines of the interface and the interface electrical connector.

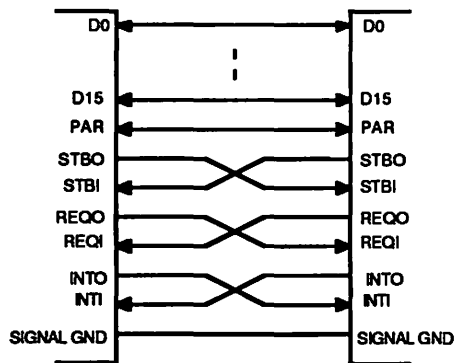


FIGURE 7: ACR-NEMA PHYSICAL INTERFACE
SIGNAL LINES



FIGURE 8: ACR-NEMA
PHYSICAL 50-PIN
CONNECTOR

On the other side of the interface, the frames would proceed back up through the layers, eventually resulting in a reassembled message. Figure 9 shows overall flow through the layers.

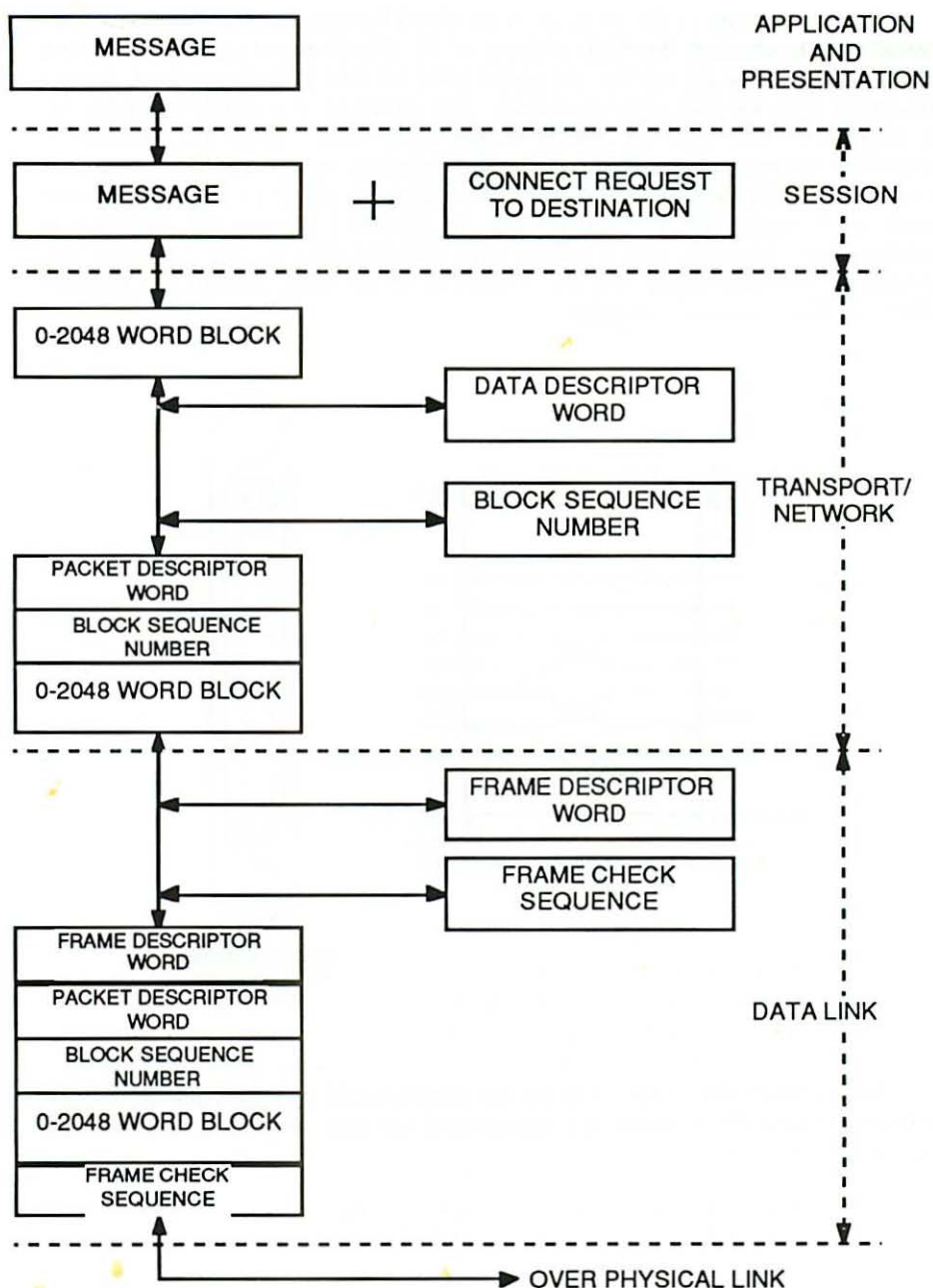


FIGURE 9: DATA FLOW THROUGH THE ACR-NEMA INTERFACE

While the Standard at first seems complex, in fact, a minimum for compatibility has been defined. This states that of the commands, only SEND need be implemented. Also, only a single channel need be supported. The full information on minimum requirements has been published by NEMA.⁵

THE OTHER STANDARDS: DATA COMPRESSION

Following publication of ACR-NEMA 300-1985, it was recognized that additional work was necessary as new requirements were made known to the Committee. New Working Groups were formed to examine these issues. Initially, data compression was assigned to Working Group IV, exchange media to Working Group V, and validation issues to Working Group VI.

The vast volumes of data generated in medical imaging departments put a strain on archival media, even optical disk. The communications systems which must handle the volume are also burdened. To help alleviate this problem, data compression has been proposed as a solution. This paper will not address the benefits of lossless *versus* lossy data compression as this was also not the task of WG IV. Rather, the Working Group sought to allow for data compression and decompression in a manner consistent with the existing Standard.

It was recognized that data compression consists of two steps. In the first the data is operated on so that it can be represented in a different way. For example, differences between pixels might be computed so that the data may be represented by these differences rather than the full pixel values. The second step consists of coding the converted data so that less space is needed for its storage. In reviewing compression methods applied to monochrome medical images, three popular conversion methods and three coding techniques were identified.

Supported conversion techniques are: differential pulse code modulation (DPCM), discrete cosine transform, and the pyramid (and its relative, the S) transform. DPCM is a differencing method which represents original data by a set of differences. The discrete cosine transform is a real valued transform for which fast algorithms exist. The pyramid and S transform are also differencing methods but compute sets of differences (in horizontal, vertical, and diagonal directions) from pixel data. The pyramid and S transforms have the useful property of producing viewable images, reduced in resolution, at each step.

Once converted, the coding methods take advantage of redundancy in the data to do the compression. The compression standard supports run length, Huffman, and Lempel-Ziv methods. Depending on how the data are quantized, the compression may be bit-preserving (lossless) or non bit-preserving (lossy). An example is in quantizing the cosine transformed data. If the quantization extends out until transform values vanish, there will be no high-frequency information lost. Truncating the transform data before this point will cut off such high-frequency

information. Loss of the high frequencies corresponds generally to a decrease in edge sharpness and diminishing of fine detail.

Another popular compression method which is lossless but does not fit well into the above list of methods is perimeter encoding. In this technique, which is used for nonrectangular images, the zero values outside the actual image area are not saved. A map describing the number of pixels per line is sent instead. This method is also supported by the compression standard.

The design of this standard is such that methods may be combined if such combination will yield more compression. The compression standard consists of new groups and elements which allow a device to describe how compression was done. For proprietary algorithms, the standard provides a structure for a manufacturer to send these data about the compression used. The structure of the compression standard was designed to be flexible and allow for future growth.

The compression standard was voted on by members of the ACR and NEMA and was approved. The document is currently available from NEMA as ACR-NEMA Standard PS-2 at nominal cost.

EXCHANGE MEDIA

Working Group V of the ACR-NEMA Committee was charged with evaluating exchange media for possible standardization. When the Working Group was formed, the most popular exchange medium was one-half inch magnetic tape. Though there was considerable interest in optical disk, there was no industry standard for it. The interest in archival as well as exchange media came from the manufacturers who preferred to write one set of software for generating exchange or archive volumes.

Since there was no consensus on optical media standards at the time WG V began working, the group decided to consider magnetic tape first. Since the charter is to consider exchange media in general, as industry moves towards standards for optical media (for example, the 5.25-inch medium) the Working Group may continue to evolve standards.

As the full ACR-NEMA Committee had done, existing standards were first reviewed. The AAPM Magnetic Tape Format ⁶ was a very good possibility, but did not address all the issues required for exchange. The manufacturers thought that too much modification of existing operating system drivers would have to be done. LANDSAT, NATO, and Japanese JAMIT were among the other standards reviewed. None was thought to be as good as the AAPM standard for medical use. The Japanese standard, in particular, had fixed-length fields. If possible, the desire was

simply to write out an ACR-NEMA data set onto the exchange medium. While manufacturers had widely differing formats for data, a common element proved to be use of the ANSI standards for magnetic tape. These covered both the physical media standardization and common labels and file structures. Using the ANSI standards, it was possible to fit the ACR-NEMA data set structure into the ANSI standard file structure with a "wrapper" consisting of ANSI labels.

As of this writing, the draft of the magnetic tape standard has been balloted, but one negative vote required ACR-NEMA to address the associated comments. This has been done, and the standard is being re-balloted. The Japanese PACS standards organization has approached ACR-NEMA WG V with a proposal for an exchange standard based on 5.25-inch erasable optical disk. This proposal is currently undergoing evaluation, and it does seem to have a fairly wide industry backing.

VALIDATION

Working Group VI was formed to examine issues related to validation of the "parent" standard. This includes both validation of the Standard itself, and assistance of those implementing or testing hardware and software for the Standard. The Working Group serves as the clearinghouse for questions about the Standard and for suggestions regarding new data groups or elements. This group also examines issues related to revision of the Standard, and defines how revisions will be compatible with prior versions. The basic guideline has been that no element would be changed or replaced unless found to contain errors.

The first revision of the Standard (version 2.0) has passed the vote of the ACR and NEMA members, and is now available from NEMA as ACR-NEMA 300-1988. This revision includes new elements for definition of an image identification hierarchy, elements added for ultrasound, and commands and elements added to support laser film writers and other hardcopy devices. All changes are compatible with version 1.0 of the Standard.

In addition to the Version 2.0 of the Standard, WG VI has published a number of engineering bulletins, errata lists, and responses to questions pertaining to the Standards. The group has sponsored a special meeting for implementers, and has published the results of that meeting. As of this writing, plans have been finalized for a hardware workshop, during which manufacturers will connect their ACR-NEMA test hardware together. The results are expected to provide a great deal of information about how well different implementations can work together, and give direction to further efforts of WG VI in assisting interconnection.

This Working Group has been the busiest, and its work continues. As discussed in a later section, the revisions for version 3.0 are presently being studied.

Two additional Working Groups have been formed to examine other issues which have been brought to the attention of the Committee. Multidimensional data was assigned to WG VII, and interfaces between hospital information systems (HIS), radiology information systems (RIS), and PACS are being developed by WG VIII. The original three Working Groups have been deactivated, though many of the members are now active in the newer WGs.

MULTIDIMENSIONAL DATA

With the increasing interest in images which are multidimensional, either in spatial dimensions or with parametric features, Working Group VII was formed to examine how such data could be accommodated in ACR-NEMA 300-1985. The Standard currently specifies that images are rectangular with the number of dimensions allowed to be "2".

This Working Group has some working proposals for member use, but has suffered from difficulty assembling all members for meetings. Some of the newer work of WG VI may supersede the activity of this group. The Working Group is on inactive status, but can be reactivated when needed, and is nonetheless seeking suggestions from interested users or manufacturers.

HIS/RIS/PACS INTERFACES

The newest of the Working Groups is defining a standard for interface of HIS, RIS, and PACS. Unlike the parent Standard, the product of WG VIII will be an upper level standard. It is thought unlikely that, in the heterogeneous computing environment formed by these systems, the hardware parts of the Standard would find much acceptance. It will most likely build around the parent Standard so that ACR-NEMA messages (or parts) may cross from HIS to RIS to PACS and back.

The necessity of this effort is based on the requirement of having certain RIS- or HIS-based data in the PACS (patient demographic information, for example), and getting PACS data (such as time of examination) back to the RIS or HIS. Allowing direct exchange reduces the problem of operator errors in transferring information between systems. Currently, much patient information has to be re-entered in the PACS. Errors lead to database inconsistency which can result in an inability to access data and in duplication of files. A similar situation pertains to PACS data which must be copied into the HIS or RIS.

The WG began by defining an entity-relationship model of radiology in order to understand what kinds of data would exist at different places in a radiology department and what the relationships between entities (such as "patient" and "report") are. This effort resulted in developing the necessary new data set groups and elements, the groups being thought of as the entities and the elements as the

attributes of the entity. The current effort is to develop a functional or operational model of radiology so that the necessary commands can be similarly defined. Work in these areas is being done with careful attention to the standards work of the IEEE Medix group as well as the HL7 and HISCC. These groups are working on standards which will affect the HIS and RIS sides of the interface.

FUTURE DIRECTIONS

The original ACR-NEMA Standard has undergone one revision, and has spawned two new standards with a third on the way. All of these have retained the structure of the parent Standard, and are compatible with it in various ways. However, as user requirements mature in PACS environments, even more changes to the Standard are anticipated.

The most ambitious effort at present is directed by Working Group VI in conjunction with Working Group VIII, and consists of examining proposals to define a version of the Standard which would operate more easily over networks. A joint development by Philips and Siemens, the Standard Product Interconnect (SPI) is one model being used. Another is based strongly on the work of WG VIII, and addresses a combination of the application level work being done by that group along with the changes necessary in the lower layers so as to support network interconnection. A definite possibility for the future is to "split" the Standard. The upper layers would be made ISO-OSI compatible, or at least more ISO-OSI-like, while retaining operability with the lower layers. The result would be a standard which could run over the existing hardware interface of Versions 1.0 and 2.0, but for applications requiring network operation, or connection between networks, could use other hardware.

This also relates to a frequently asked question about availability of ACR-NEMA implementations. As of this writing, implementations for VME bus to ACR-NEMA, IBM PC/AT bus to ACR-NEMA, and Digital Equipment Corporation Q bus to ACR-NEMA exist, though some are admittedly prototypes. The Japanese manufacturers have indicated that they are working on both full ACR-NEMA implementations as well as a minimum requirement version they call MIPS. Sanctioning the use of the ACR-NEMA data structure over non-ACR-NEMA interfaces creates a problem in that it has the potential to result in a multitude of hardware-incompatible devices. However, many of the ACR-NEMA Committee members see this change as a necessity as it will allow the ACR-NEMA data structure to be more widely used. The hardware interface will still be available, and for applications which require its speed, is still highly desirable.

THE USES OF THE ACR-NEMA STANDARDS

The primary uses of the ACR-NEMA Standards are dependent on what functions are being supported. The 300-1985 and 300-1988 interface standards are designed primarily to connect image generating equipment to other devices. Those other devices may include network interface units (NIU), teleradiology transmitters, laser film writers, diagnostic workstations, or even another piece of imaging equipment. In a PACS, the most likely connection is to an NIU or data acquisition device (AD). In this instance, the ACR-NEMA interface is on one side of the NIU or AD and the PACS network connection on the other. If the network does not support ACR-NEMA data structure directly, the NIU or AD then serves as a protocol converter.

A frequently raised point about the interface Standard is that its performance dictates significant processing power, and that unless a low cost version is available, it is unlikely to be used on equipment which costs only four to five times what the interface does. This is a valid criticism, and can be addressed in two ways. The first is that low-cost interface hardware is becoming available. The PC/AT card version is a good example. This would allow construction of an NIU or AD based on a PC rather than a minicomputer.

The second solution involves architecture of the PACS. While it may not be cost-effective to use a separate ACR-NEMA interface on each piece of equipment, it may be economical to use a single interface with multiple devices connected to it. Examples are in ultrasound and nuclear medicine. In the former, multiple video outputs (or digital, if available) could be connected to a central computer which would manage the data from the machines so as to keep the images sorted by case. This computer would have a single ACR-NEMA interface for PACS connection. Nuclear medicine would be similar, and is more likely to evolve this way since many nuclear medicine departments are already networked to a central computer system. These approaches are not very different from systems which currently use a shared laser printer with a computer front end to keep the images sorted out.

The data compression standard will be of value in reducing PACS storage and network bandwidth requirements. Even a lossless compression of 2:1 doubles archive capacity. The use of the lossy compression techniques requires that those who will be using the expanded images accept this limitation. Since the techniques are often computationally intensive, to be of value for reducing network bandwidth some form of hardware for fast compression and expansion will be required. Research on lossy compression and hardware for performing the algorithms is presently underway. It may be possible to use compression selectively, compressing images only after they have been interpreted or only if they are being sent to non-diagnostic workstations.

The exchange medium standard, which currently supports magnetic tape, will find use in inter-institutional exchange. Though engineers have been predicting the demise of magnetic tape for some time, it manages to remain heavily used, even if not very popular. The emergence of a standard for optical disks, particularly the 5.25-inch format, will eventually result in phasing out magnetic tape for exchange. The 12-inch optical medium has, unfortunately, progressed quite far with no widely accepted standard, so that standardization now is unlikely. Industry has had more success in developing support for the smaller medium. Another potential use of the exchange medium standard is for use in a per-patient or personal health data system. In these proposed systems, each patient's medical record information is written on a small, removable medium (probably optical). The idea is to allow the patient to carry his or her data around to different healthcare facilities as needed. The necessity of a standard for this application is self-evident.

Communication between the different information systems in a medical facility could benefit from use of the standard which is being developed by WG VIII. The HIS/RIS/PACS standard will of necessity be an upper-layer one. It will, along with standards efforts in the HIS and RIS communities, help promote the concept of an electronic medical record. This idea continues to grow in popularity as the advantages of a record which is amenable to database operations become more clear. As healthcare becomes more regulated, the production of reports demonstrating efficacy or documenting the necessity of treatment will be an increasing burden if paper records have to be searched manually to retrieve the necessary information.

CONCLUSION

In the seven years since its formation, the ACR-NEMA Committee has succeeded in producing an interface standard which is beginning to be used in a number of PACS. This standard has undergone one revision, and changes for the next version are being studied now. In addition, they have written standards for image data compression and exchange media, and are working on a standard for HIS/RIS/PACS interfaces. These efforts are guided by the radiologic community as well as by representatives of industry. The collaboration between those who establish requirements and those who must build equipment to meet them has been very productive.

The ACR-NEMA Committee welcomes comments on all of its efforts. In particular, WG VI is interested in hearing from those who are building ACR-NEMA interfaces and WG VIII in those who are working on other standards for healthcare information management. The various Working Groups can be contacted through:

National Electrical Manufacturers Association
2101 L Street, NW Suite 300
Washington, DC 20037
Attention: Staff Executive, MedPACS Section
Phone: (202) 457-1965

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Image Storage Organization

R. Hindel

Philips Medical Systems N.A., Shelton, CT

Image storage and image access are important aspects of PACS and deserve much attention by the system designer. The reporting radiologist has very fast access to a bank of images and has seemingly already optimized the process of information transfer: visual input and verbal output. His expectations of PACS were expressed a decade ago as faster and more reliable access to the diagnostic image bank. In addition such access should be provided from various locations. Technical implementations, though, are still falling short of meeting such expectations.

Optical storage technology promised a decade ago to offer high density digital image storage of archival quality at low cost. [1] . We find now that magnetic data recording technology has made more progress than optical technology and offers fastest data rates at lowest costs for removable media. The isolated storage device, however, does not determine the effective image access time but the overall organization. In order to better define the task a typical workload of a PACS radiology department will be assumed.

The interrelationship between resolution, storage capacity, access time and cost can be seen in Fig 1, which cites AHA data [2] and lists the number of procedures per bed and year for larger US hospitals. For plain film radiography we find that 124 procedures are performed per bed and year. The next columns show Images per bed and year, square feet of film, images per procedure, data volume per image (kB/I) and MB/b/y. According to these projections a 500 bed hospital would produce about 3500 MBs of image data per day.

SYSTEM ARCHITECTURE

While it is generally assumed that PACS is a distributed system, several implementations are possible and have been described [3, 4]. A system architecture which resembles that of a conventional department with a film library and a film archive is shown in Fig 2. It is topologically a "star" configuration with the "Digital Image Library" at the hub and input devices (modalities) as well as output devices (workstations) at the rim. This, incidentally, is the topology of the "CommView" PACS, developed by AT&T and marketed by Philips.

Data quantities as listed in Fig 1 are assumed to be supplied by the respective modalities and converge ultimately on the Image Library. The conversions of the original modality image format into a compatible format will not be discussed here, but it is assumed that such compatibility exists and also that no data reduction algorithm (such as compression) is applied. Two types of transfer paths are assumed : a direct path, where images and all relevant patient information are transferred directly into the Image Library and a second path where images are transferred into a workstation. Throughout this paper the emphasis is on images while generation, transfer and storage of patient data is assumed to be implemented in a satisfactory manner.

It is furthermore assumed, that the primary diagnosis is established at the modality in question. This assumption may not be acceptable to some promoters of PACS but clarifies the underlying concept of PACS. For CT, MRI and US images this assumption poses no challenge. For radiography, however, as well as R & F and DSA images PACS is generally assumed to offer advantages also for the diagnostic process. In particular Teleradiology is only meaningful if it can handle traffic of diagnostic images and not only "review images". Still, this paper deals only with the organization, traffic and storage of images for which the primary diagnosis has already been established. Target of optimization is

*data volume / image
kilobytes / image
megabytes / image*

PRODUCTIVITY PROJECTIONS

	<i>proc/b/y</i>	<i>I/b/y</i>	<i>sqf/film</i> sqf/b/y	I/proc	kB/I	MB/b/y	%
Rad.	124	354	394	2.9	5000	1770	70
Contr.	20	207	198	10.4	1000	207	8
Spec.Pr.	4	285	94	71.3	1000	285	11
						0	0
US	10	360	31	36	250	90	4
N.Med.	7	98	6	14	33	3	0
CT	9	205	33	22.8	500	103	4
DSA	5	81	18	16.2	500	41	2
MRI	2	64	7.3	32	250	16	1
						0	0
Total	181	1654	781.3	9.1		2514	100
av.:	14 MB/proc		1.5 MB/I				
	4.3 sqf/proc		3.22 MB/sqf film				
	9.1 I/proc						

Fig 1

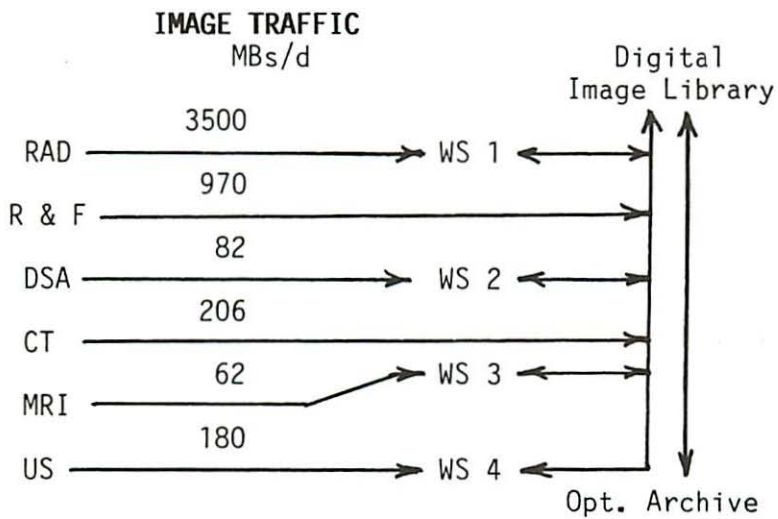


Fig 2

access to archived images by medical specialties as well as authorized persons outside the hospital, including referring physicians.

Images have to be transferred into the PACS environment with minimal disruption of the revenue generating operation of the modalities. This means that the data transfer rates into the PACS environment must match the average acquisition rates and may even have to match the maximum acquisition rates. It is a further assumption that image data are not transferred back into the generating modalities. This assumption is increasingly endorsed by experts who recognize that an omnipotent image processing workstation is unrealistic.

The traffic out of the Image Library into workstations is bidirectional because edited or postprocessed images will also be deposited in the Image Library. These workstations are information centers for authorized PACS participants and supply images related to diagnostic cases as an important type of information.

There is no direct connection between workstations, but only via the central Image Library. This arrangement may again run counter to some desires but is intended to preserve the authority of the reporting modality experts. Only if and when such experts have released images for which they are responsible can others gain access via the Image Library. This restriction is similar to good practices in a department.

The Optical Jukebox is the long term archive and is attached to the Image Library. It will hold image data of nonactive cases on removable media. As mentioned above the data base controlling search and retrieval is not part of this discussion, but it should be assumed that it exists and performs satisfactorily.

INPUT IMAGE DATA RATES

Both data rate and data quantity vary from modality to modality. Digital cine for cardiac examinations produces a data rate of at least 8 MB/s. This rate is equivalent to 30 images of 512 by 512 resolution and 8 bits data depth. (Fig 3). This data rate can be stored

on fast parallel disks but an examination may fill a large disk with the result that the next examination has to be delayed until the data have been transferred into a permanent storage. This second storage has often a much lower data rate. Although optical technology development was expected to produce equipment which can offer a data rate of 50 Mb/s (6.3 MB/s) [5], such development has not yet occurred. Magnetic removable storage, has been demonstrated which can handle such data rates [6, 7].

Optical tape [8], as recently announced, offers a sustained data rate of 3 MB/s, but even this is too slow for on-line digital cine recording.

CR (Computed Radiography) is producing a large amount of image data but at a rate of only 83 kB/s. The limitation is the readout of the storage phosphor which is determined by a physical time constant. It is unlikely, that the readout time can be significantly shortened.

Ultrasound in dynamic mode supplies data at cine rates but with less depth than cine angiography.

Conventional video recording suffices for on-line storage prior to data editing.

Nuclear cardiology also produces cine data but of limited resolution so that magneto-optical recording or even WORM recording would suffice.

CT and MRI are already offered with optical WORM drives and pose no challenge.

COMPARISON OF REMOVABLE RECORDING MEDIA

Fig 4 list some of the most significant media for medical diagnostic recording. The diskette (floppy) is still used but has limited capacity, although new developments will increase both capacity and data rate [9]. Removable magnetic disks are relatively expensive and of limited capacity and data rate. Magnetic tape is listed as reliable medium, certified for archiving of important information. Helical tape, capable of recording at high data rates is offered by two companies:

Acquisition Rates

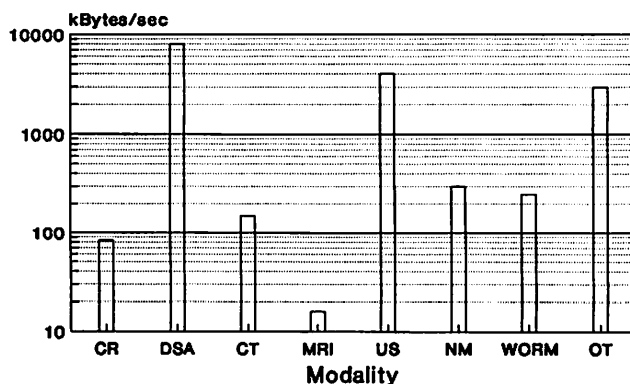


Fig 3

COMPARISON OF REMOVABLE IMAGE STORAGE MEDIA

Storage Method	capacity MBs	medium \$/MB	Sys.cost \$ k	Data Rate MB/sec	access sec
Mag. Diskette	1	0.1	0.2	0.14	5.0
Mag.Disk	16	3.75	6.0	1.2	0.06
Mag.Tape 2400' 6250 B/inch	175	0.29	20.0	1.25	60.0
Helical Tape Honeywell	5000	0.002	40.0	2.0	45.0
Helical Tape Sony	770000	0.0003	250.0	32.0	30.0
Mag.Cartridge IBM 3850	500000	5.0	2400.0	0.875	16.0
Optical Disk 12 inch	2000	0.2	80.0	0.25	0.2
Optical Disk 5 1/4 inch	200	0.325	3.0	0.1	0.2
Optical Tape	1000000	0.01	220.0	3.0	28.0
Opt. Jukebox	128000	0.2	135.0	0.25	15.0

Fig 4

ARCHIVING OPTIONS

500 bed hospital, 5 GB/d, 363 procedures/d,
121 patients/d

option 1: every patient has a 500 MB disk
121 disks must be loaded daily
30,250 disks per year

option 2: Jukebox with 100 disk, 2 GBs each
2.5 disks/d to be loaded
625 disks per year

option 3: Terabyte optical tape system
5 GBs need 5 m of tape
1.25 reels per year

Fig 5

Honeywell has some time ago announced the VLDS and Sony has recently shown a "Digital Instrument Recorder" with a recording rate of up to 32 MB/s. This rate would suffice for recording 1000 by 1000 pixel images at video rates.

Optical disks of the WORM type are still slow (.25 MB/s) [10], but the optical tape system manufactured by Creo offers a sustained data rate of 3MB/s.

ARCHIVING OPTIONS

Short term archiving of images of active cases is performed by the Image Library. The average length of stay in USA acute care hospitals is 6 days which means that the Image Library should be large enough to hold 30 GBs of image data. If access to old image must be offered some of the images archived in the Jukebox will have to be transferred into the Image Library. A first option is reduction of the digital radiographic cases by using CR mainly for ICU and emergency cases. A CR system can handle maximally 480 films per day (120,000 per year) but realistically only a half of this can be processed so that the daily RAD data quantity is reduced from 3500 to

1200 MBs. The required Image Library capacity is then 22 GBs. Even this magnitude is too large for magnetic disk storage so that access to the Jukebox will be required even for active cases.

Optical Jukeboxes offer storage capacity up to a Terabyte (1000 Gbs) and access time of the order of 6 - 10 sec. The optical tape system by Creo has slower access time but offers higher data rate and reduced cost. There is renewed interest in distributing image archiving over many disks whereby every patient would have an optical disk assigned. Fig 5 lists three options for a "filmless" 500 bed hospital. The daily procedure load of 363 is represented on the average by 121 patients. For a full year this amounts to 30,250 disks which have to be stored, accessed and updated.

Option 2 would perform long term archiving on a Jukebox with 100 disks each of 2 GBs capacity. 625 disk would be needed per year or 2.5 disks average per day.

Option 3 uses the Terabyte optical tape system which can stored the yearly workload of 1,250 GBs on 1.25 reels of tape. The daily data quantity would only take up 5 meters of tape.

Obviously there are advantages and disadvantages with any one of these three options, but technology has progressed to the point that such options are available and can be considered for a realistic implementation of PACS.

CONCLUSION

If a primary requirement of a useful PAC system is fast access to a large number of images organization of image storage has be optimized. This will require assessment of the various magnetic and optical storage systems but may also require a novel approach to storage space allocation. Fast magnetic disk offer already fast access to large data blocks. A review of the storage requirements of a "filmless" radiology department leads to the conclusion that short term archiving all of the radiographic images would become complex and very

expensive. The suggested solution is optimized design of the long term archive for fast access and reduction of the digital radiographic workload.

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Q-RSTAR Digital Image Management and Transmission

J.L. Taaffe, M. Kaldis, J. Gahm, et al

Department of Radiology, Massachusetts General Hospital,
Boston, MA

Introduction

If the MGH Q-RSTAR PACS is to be viable as a clinical system, it ultimately, will archive approximately 4-5 million megabytes of image data per year, yet be called upon to provide very quick storage-to-screen access times for individual images, each typically containing 8-16 megabytes of data. In designing Q-RSTAR, it became clear that any discussions about the image storage system without full consideration of the communication methods and algorithms was impractical. This paper will describe four areas of development within the Q-RSTAR system. They are: statistical image caching, distributed image storage and management, local area networks, and wide area networks.

Statistical Image Caching

It is well known that, in general, cost for a particular type storage device increases dramatically with decreasing access time and increasing throughput. An archive consisting solely of solid-state memory may have exceptional performance but suffers from astronomical cost. Conversely, an archive based upon ultra-high density helical scan magnetic tape drives has a low cost per byte but suffers from very poor performance.

Given the semipredictable pattern of image retrieval within the hospital environment and the obvious relationship between storage cost and performance, the following question becomes conspicuous: Can the image archive be constructed so that images are moved from slow, inexpensive storage to higher performance storage in anticipation of their actual use, as a means of obtaining high performance at an affordable cost?

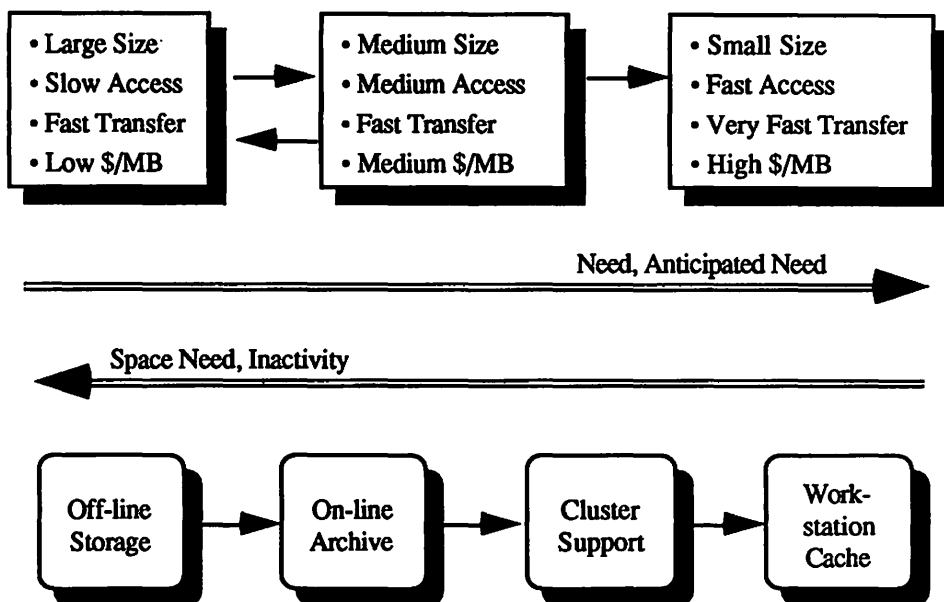


Figure1 : Caching and Preload

Specifically, can image data be moved from slow, inexpensive storage based on need or anticipated need to high performance storage elements? Conversely, can image data be purged from the high performance elements based upon space-need or inactivity? Figure 1 offers a schematic representation of this concept. In the Q-RSTAR system, the most inexpensive storage devices are the removable media (for example optical platters and magnetic tapes) that have been placed off-line. Moving right in the diagram, mounted volumes are clearly more accessible but occupy resources (for example an optical drive or slots in a Jukebox). In the Q-RSTAR system, a device named the 'Cluster-support' unit contains, among other devices, a 3.4 gigabyte, high-performance, parallel transfer magnetic-disk-array. This magnetic-disk-cache is intended to quickly service requests from workstations needing image data. Additionally, within a Q-RSTAR workstation is a small (4 to 16 megabytes) solid-state based image buffer (or cache) allowing repeated requests for a small subset of images to be serviced quickly and locally.

The goal is to move images along this hierarchy so that the images arrive at the high performance elements just as the user needs them. The key to achieving this goal is in implementing a set of algorithms that anticipate where and when images may be requested.

In the process of rendering patient care, many events take place that indicate the future use of radiological images. Scheduling a patient for radiological exams indicates a strong probability for prior exams to be recalled. Obviously, the

completion of an exam indicates that these images will be accessed soon. Viewing the first image of a CT series is an indication that the others soon will be requested. The Q-RSTAR system uses these techniques to manage its image archive and receives its primary caching information from the Department's Radiological Information System, DecRad (a Digital Equipment Corporation product).

Distributed Image Storage

Since Q-RSTAR will service many separate facilities located throughout the Boston metropolitan area (e.g., Boston, Charlestown, Somerville, and Cambridge), the system supports a distributed image database. For reliability, it is useful to maintain copies of currently active images within more than one archive unit. Again, this necessitates the need to maintain a distributed database.

The basic "raw materials" needed to implement this distributed image storage scheme are *Storage-units*. A storage-unit is simply a device that is capable of storing strings of bytes representing images. Storage devices can be graded according to several criteria: (1) cost/megabyte of capacity; (2) typical access time to store or retrieve images of various sizes; (3) reliability of media; (4) reliability of device (e.g. MTBF); (5) the communication protocols through which they are able to send and receive images. Q-RSTAR is able to integrate a wide spectrum of storage devices with different configurations of these parameters.

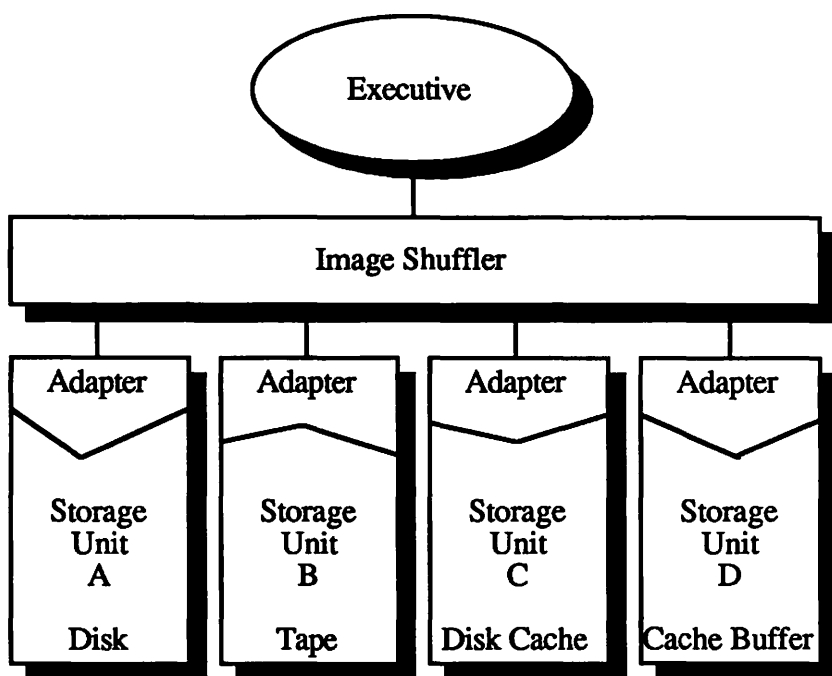


Figure 2: Distributed Caching

The Q-RSTAR distributed image database provides a framework for integrating all available Storage-units into a single distributed image database and cache regardless of where the Storage-unit is located. Figure 2 shows the structure of the distributed image database. In the figure Storage-units A and B may reside on a VAX computer, Storage-unit C may be a parallel-disk-farm hosted off of a Macintosh, and Storage-unit D, a buffer residing in a user's workstation.

As shown, each Storage-unit's communication channel is "wrapped" in an adapter which gives it a common interface to higher level software. A common layer of software called the "Shuffler" arranges transfers of individual images between different storage facilities using available communication channels, while a still higher layer, called the "Executive" implements the caching strategy and image management functions.

Local Area Networks

For this caching strategy to work, the bandwidth between various Q-RSTAR components, in particular between the magnetic-disk-cache located in the Cluster-Support unit and the workstations, should be high. We considered a number of LAN'S such as FDDI (Fiber Distributed Data Interface) and Ultranet (Ultranetwork Technologies Inc.), to name a few, but they offered a poor price-performance ratio in relation to the number of units needed for the deployment

schedule planned for 1990 and 1991. As described in other papers, the intra-institution communication substrate for Q-RSTAR is based upon the concept of a Dual LAN as shown in figure 3. An industry standard, Ethernet, is used to carry command & control information between the Cluster-Support unit and the workstations. A high performance, but functionally primitive, optical LAN, based upon Advance Micro Devices Inc. TAXI chips, carries image data. This approach has met the required price-performance goals.

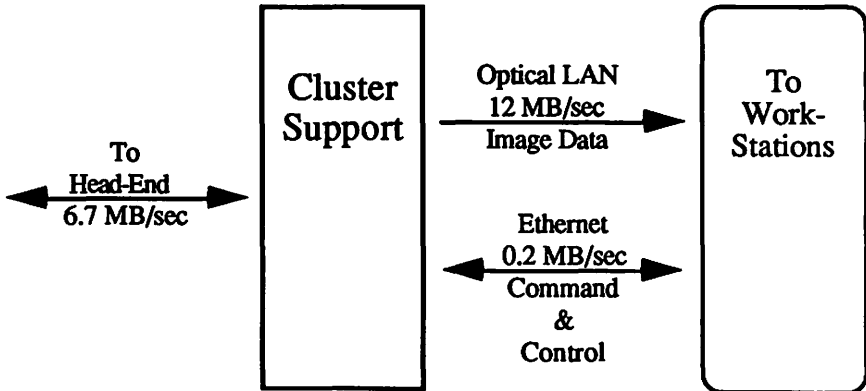


Figure 3 : Dual LAN

Wide Area Networks

The MGH department of Radiology is itself geographically distributed and serves a number of geographically distant affiliated institutions. To meet the needs of high speed data interchange between the various Q-RSTAR system locations both 45 megabit/second DS3 and 1.5 megabit/second T1 circuits have been run to the locations as shown in Figure 4. Bridges and gateways interface the LAN and WAN (wide area network).

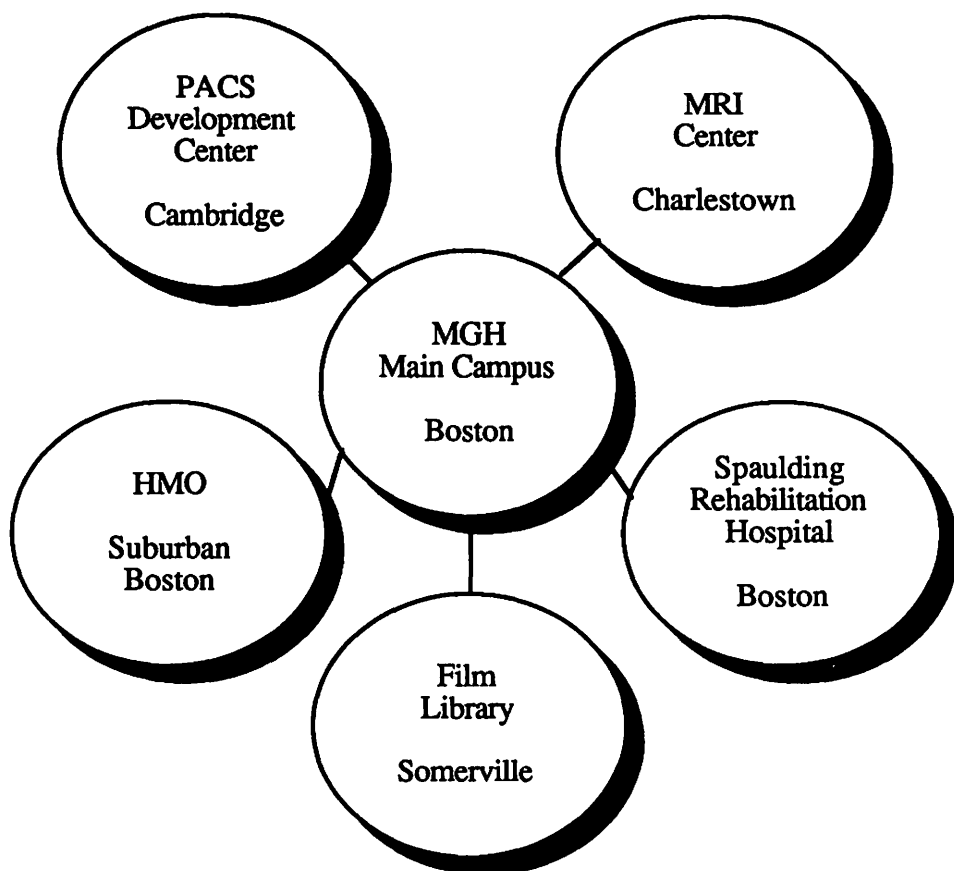


Figure 4: Wide Area Network

Overall System Interaction

The primary goal is to create a system that provides for image availability at a reasonable cost but with high performance and throughput in a wide-area distributed computer environment.

In this system all archives (long or short term) and intermediate storage elements, whether they be disks, tapes (both on-line and off), or computer memory buffers are treated as Storage-units. A Storage-unit presents a common interface regardless of the media or technology. Connecting all Storage-units is a directed graph of communication 'pipes' provided by either the LAN'S or WAN'S managed by the system's Shuffler. The Shuffler's responsibility is to manage all pipes and to orchestrate the orderly transfer of data from one Storage-unit to another. At the top of this pyramid is the distributed image management system's Executive. The Executive uses heuristics about 'how' the department operates to service requests for image data availability in an anticipatory manner.

Additionally, the Executive manages the redundant placement of active images on a multiplicity of Storage-units.

Many systems have LAN'S, WAN'S, distributed storage, and caching strategies. It is felt that the unique contribution of Q-RSTAR is its effort to integrate all available storage facilities and communication resources into a unified framework.

Classification of Radiological Images for Self-Adaptive Optimal Compression Purposes

u/375

R. Kanz, F. Gille and C. Wehenkel

Centre de Recherche Public Henri Tudor, LUXEMBOURG

J. Duchene and J.F. Lerallut

Universite de Technologie de Compeigne, FRANCE

Abstract :

In the domain of radiological image compression it is known that the resulting distortion due to this transformation is a very critical point. But it is also known that today with the actual applied technologies in PACS it is nearly impossible to store and transmit in an efficient way this huge amount of medical imaging data. Compression is therefore an essential mean of reducing this large storage requirement and the related archiving and transmission charges.

A new adaptive image oriented methodology is presented in this paper for radiological image compression which consists in characterization and classification of radiological images leading to an optimal choice of encoding algorithm for the various image classes.

The classification in itself is based on textural features and uses a Karhunen - Loeve expansion and discrimination which provide very interesting results

Because of the large number of image classes present in radiology we developed a method called "discriminating pyramid" which consists in a succession of discriminant classifications, and which ends in obtaining a well-defined image class with the appropriate encoding algorithm.

1. Introduction

Quite recently PACS (Picture Archiving and Communication System) [1] has become more and more a reality in a modern hospital.

The justification of such an image management system is based on different factors:

- more efficient diagnose possibilities (quicker retrieval of older archived images, possibility of postprocessing of numerical images, ...)
- less films are produced, a more rational way of management in a radiology department

- efficient image communication between an in geographical separated units distributed radiology department

But this new concept involves the transmission and the storage of huge amount of data, in a world where the number of radiological image producer and related examinations is still increasing. The spatial resolution is also growing in an important way, specially in the field of conventional digital radiology (about 2048 x 2048 pixels => about 4 Mbytes/image).

Even if the technologies related to this recent concept are going to be more and more able to support such a technological challenge, there still are problems to fulfill an efficient management and manipulation of such amounts of data.

And by this reason image compression is a very important component of a PACS [1][15].

But specially in medical images, when using efficient irreversible compression methods, distortion is a very critical point of acknowledging whether yes or not a method is applicable to a special kind of medical image [15]. And there are no adequate objective or analytical methods yet of evaluating distortion, so it is often preferable to use ROC studies to have a subjective criteria of the performance of an algorithm.

Also compression must be for the user an invisible task demanding of him less as possible interaction.

In this paper we give first a global overview of different kinds of compression methods. In a second chapter we give a new approach of classification of medical images in function of their textural content and then relating the most efficient encoding algorithm an its compression ratio to this class of image.

In a third chapter we give an example of context sensitive segmentation permitting to encode most effeciently the different kinds of information types present in an image (background, anatomic region, text)

2. Global Overview of Image Compression Algorithms

During the last 20 years one could observe a large interest in research of developing new methodologies for image compression [2] applied in fields as different as aerospace imaging, industrial image processing, video imaging and finally medical imaging.

Generally image compression methods are subdivided into two classes:

- exact or error-free encoding
- irreversible encoding

Exact or error-free encoder are often very efficient for non-natural images as graphics or synthetic images. For natural images like medical images they give compression ratio about 2 to 3.

More efficient are irreversible compression algorithms, permitting in function of acceptable distortion to obtain compression ratio of about 10 to 15.

But there is an important difference, that is the fact that irreversible compression algorithms are more complex and so need for time acceptable compression a more sophisticated hardware architecture.

2.1 Error-free or Exact Encoding

We give in this chapter the principles of the often used error-free compression algorithms.

The main advantage of these methods is that they are easily implementable and that they don't be based on a complex theory.

Therefore this algorithms can even run on not sophisticated architectures, but in medical image compression when used in a direct form they don't give important compression ratio (2...3).

° Huffman Coding [4]

The Huffman coding (entropy coder) uses the fact that in a grey-level image the probability distribution of grey levels is normally not uniform, and so this method attributes shorter codes to those levels, which have the most important probability of occurrence in the image and longer codes to those levels having less important occurrence probability. This implies that one obtains variable length codes and so a necessary condition is to respect the prefix rule, giving the possibility to separate concatenated codes afterwards on the receiver side. For an eight-bits level image the most important compression ratio one could obtain is 1bit/pixel (uniform grey-level image).

° Run Length Coding [27]

Run length coding uses the fact that if successions of same valued pixels are present in the image, they can be coded by a pair of values, where the first indicates the grey level and the second the occurrence or frequency of this.

If a certain threshold value of a run is not present a special flag indicates that the following n words are not encoded.

The image can be searched or scanned by different ways, like row by row or column by column.

The decoder then makes a restauration of the different runs which were present in the original image.

Different kinds of preprocessing operations of the image give more efficient run-length coding , as shifting or substraction operations.

There exists an other family of encoders based closely on run-length coding, but looking for 2_D runs.

This method is commonly called quadtree [28] coding.

° *Predictive Coding [2]*

The aim of this method is to make as well as possible a prediction $\hat{a}(i,j)$ of the encoding pixel $a(i,j)$ and then to store with less bits as possible the prediction error $e(i,j) = a(i,j) - \hat{a}(i,j)$ instead of the normal pixel value.

The predictor itself can be a linear combinaison of the neighboring pixels or a more complex adaptative predictor.

There exists a lot of variants of how designing an optimal predictor (ex.: maximum likelihood predictor, minimum mean square predictor,..).

2.2 Irreversible Coding

Irreversible coding represents a more efficient coding family permitting to get more important compression rates, but introducing a distortion error in the decoded image.

Irreversible coding is done either in the spatial, frequency or in a spatial-frequency domain [2].

The goal is to eliminate the present correlation in the original image space [3] by a transformation and thus obtaining a more compact representation of the image in a new space, where then the critical point is to quantize as well as possible the resulting parameters or coefficients either in by scalar or vector method.

Most of these methods use an error-free coder after quantization of coefficients, for optimizing the final storage of them. This operation is commonly called hybrid coding.

Generally, to evaluate the performance or the quality of the coding operation one uses different features like:

- Mean Square Error :

$$MSE = \sum_i \sum_j [(Po(i,j) - Pc(i,j))^2] \quad (1)$$

Po original image, Pc coded image

- Signal to Noise Ratio:

$$\text{SNR} = 20 \log_{10}(E[x(i,j)]^2 / \text{MSE}) \quad (2)$$

In literature one also can find more sophisticated measure features like the WMSE (weighted mean square error) [10] which tries to ponderate the coefficients in function of an eye sensibility criteria.

But often these objective features don't give satisfaction in evaluating the performance of a compression method with its related compression ratio, and so it is often more useful to apply ROC studies (Receiver Operation Characteristics) to evaluate the performance by a subjective method.

We will describe here in a very short way different irreversible algorithms like:

- Cosine Transform
- Bloc Truncation
- Vector Quantization
- Subband Coding

° *Discrete Cosine Transform (DCT) [3]*

The cosine transform represents today the most used irreversible coder for several reasons:

- the long experience and the good characteristics of DCT this implies that a lot of optimizing steps repose on this method (very proach to the Karhunen-Loeve transform)
- it is on the DCT algorithm that the choice of the ISO/CCITT group was made for standardization of still image compression
- a lot of hardware implementation exists today on the market permitting to fulfill DCT compression in a very rapid way

The two dimensional cosine transform and its inverse can be written in the following way:

$$F(u,v) = 4/N^2 c(u) c(v) \sum_m \sum_n x(m,n) \cos[\pi (2m + 1)u/2N] \cos[\pi(2n + 1)v / 2N] \quad (2)$$

$$x(m,n) = \sum_u \sum_v c(u) c(v) F(u,v) \frac{\cos[\pi(2m+1)u/2N]}{\cos[\pi(2n+1)v/2N]} \quad (3)$$

$$\text{where } c(u), c(v) = \begin{cases} 1/\sqrt{2} & \text{if } u,v = 0 \\ 1 & \text{if } u,v = 1 \dots N-1 \end{cases}$$

The computation of the cosine transform is normally based on a FFT calculation [5], first applied on the rows and then on the columns, which permits to obtain acceptable computation time.

The cosine transform is either applied on the whole image size (Full-frame DCT)[1] or on a blocks subdivided image [6] of for example [8x8] submatrices.

Most quantification methods pass by an optimized adaptative [6] bit allocation approach, either making scalar or vector quantization of the resulting DCT coefficients (see Vector Quantification).

Of interest are one-pass methods (ADCT of the ISO/CCITT group) [7] because of the optimization of computation duration and hardware requirements.

° *Bloc Truncation Coding* [2]

The aim of the bloc truncation algorithm is to code subimages of an [4x4] array size for example in a way to conserve two statistical moments (ex.: mean and variance) and by that way to make a local texture modelisation for compression purposes.

In a first step the mean m and the variance v of the bloc are computed:

$$m = 1/N^2 \sum_i \sum_j p(i,j) \quad (4)$$

$$v = 1/N^2 \sum_i \sum_j [p(i,j) - m]^2 \quad (5)$$

N^2 number of pixels of a subimage

In a second step the pixels of a bloc are quantized to two levels by the mean m as threshold such as 1 if the pixel $p(i,j)$ is greater than m or 0 if $p(i,j)$ is less or equal than m .

Then m and v are quantized, both with the binarized bloc represent the coding information.

For decoding such a bloc, we must first evaluate q , the number of 1's of the binarized bloc, and then obtaining $p = N^2 - q$ the related number of 0's.

Then the two quantizer levels are computed (which preserve the mean and variance of the original bloc):

$$L_0 = m - \sqrt{[v \ q/p]} \quad (6)$$

$$L_1 = m + \sqrt{[v \ p/q]} \quad (7)$$

The last step consists in replacing each 1 in the binarized bloc with L_1 and each 0 with L_0 .

In an ordinary form this algorithm permits to obtain a 2 bits/pel bit-rate, if mean and variance are quantized to 8 bits each and no other method is used to compact the subimage codes.

The BTC algorithm is first very simple for implementation purposes and secondly reproduce very well sharp edges and impulsional texture like it is the case for echographic images.

° *Vector Quantization [9]*

Vector quantization was first introduced in the early 80's by Linde, Buzo and Gray [8], who developed a new approach of VQ design for the domain of speech coding.

This algorithm is commonly called the LBG-algorithm and is still today a reference in VQ design.

The base of this approach lays on the rate-distorsion theory of Shannon, which points out that one can obtain better performance with VQ than with scalar quantization in the meaning of distorsion and compression ratio.

The basic principles lay on the operation to obtain an optimal codebook, which permits to encode in an accurate way a sequence of spatial or frequency parameters, instead of coding coefficient after coefficient like it is in scalar quantification.

The VQ-operation consists in first assigning to a k -dimensional vector $x=(x_0, x_1, \dots, x_{k-1})$ (x in the spatial or a transformed domain) a channel symbol $g(x) \in M$ (set of channel symbols), which distance is the nearest to the encoding vector x , and this by an encoder g .

At the receiver side the decoder β assigns to a channel symbol $v \in M$ a value of a reproduction alphabet $\hat{A}$.

If M has m elements then $R = (\log_2 m)$ represents the rate of the quantizer in bits per vector and $r = R/k$ is the rate in bits per symbol. Distorsion can be represented by the average euclidean distance between the original vectors and the reproduced vectors.

In image compression vector quantization is either applied in the spatial domain by coding blocs of pixels or in a transformed domain

like DCT by regrouping in different ways DCT-coefficients to arrays and then coding them by the nearest vectors of a codebook [9][10].

° Subband Coding [11]

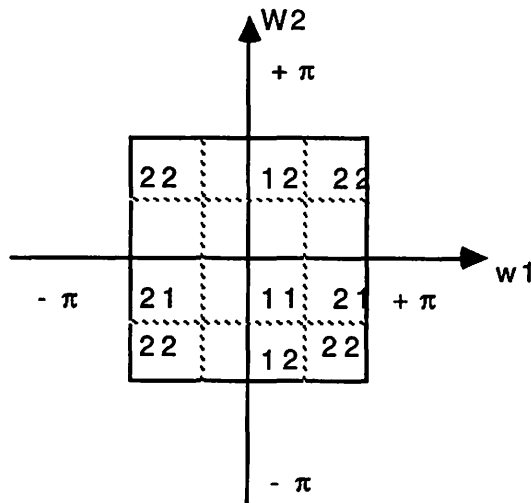
The basic of subband coding is to split up the frequency band of the image signal and then to downsample and code each subband separately or related, using a coder and bit-rate allocation closely matched to the statistics of the considered frequency band.

For this reason the characteristics of this method are those of a multi-resolutional spatial-frequency decomposition.

Normally a 16 band system [11] is used for this purpose where FIR-filters are applied to approximate the ideal subband filter.

Therefore the QMF (quadrature mirror filter) is used which cancels out the usual present aliasing (frequency gap) effect.

For obtaining these 16 subbands the initial image is first partitioned into 4 bands.



Partition in 4 subbands by QMF

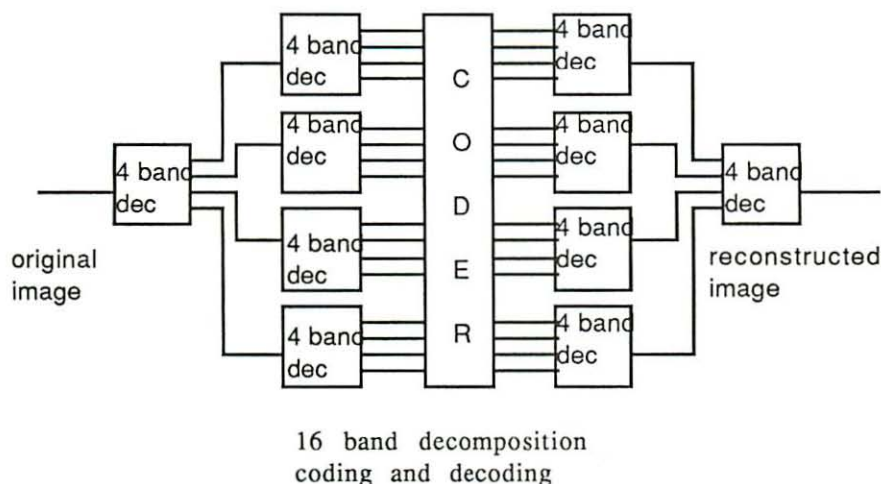
Each of these four subbands is then demodulated to base band by a subsampling operation.

For obtaining a 16-band representation each resulting band of the first filtering operation is partitioned again in four bands by QMF.

For decoding inverse operations are done.

In a 2_D approach QMF (separable product) can be represented as follows:

$$H_{i,j}(w_1, w_2) = H_i(w_1)H_j(w_2) \quad 1 \leq i, j \leq 2 \quad (8)$$



The subbands can be coded either using DPCM [11] with bit allocation to approximately minimize the mean square error, or by encoding for example the 16 subbands with vector quantization (exploiting dependencies between subbands) [12].

There are two other families of image coder, closely related to this method, called the Laplacian Pyramid Coding [13] and the Wavelet Coding [14].

3. Classification of medical images for optimal coding purpose

Radiological images are produced from very different kinds of image sources, being based on different physical principles.

This causes that each type of image differs in a visual way concerning their basic textural appearance.

For different types of images and diagnoses related to this modality, the radiologist either looks for example for edge-like details (stenose in angiography) or for texture-based details (tumors) or for very small punctual details (micro-calcifications in a mammography), and so

image compression can create distortion which could deteriorate this information.

Thus it is important to define the best compression algorithms with its related compression ratio for each image class [26].

This can be done by a ROC-study with radiological experts showing different kinds of compression methods for the different image classes. The classification of radiological images which will be described in the further lines is essentially based on textural features [21] of different natures:

° *Gray Tone Spatial Dependence Matrice or Cooccurrence Matrice (GTSDM) [16]*

The method of cooccurrence matrices describes the image in function of a spatial dependence of neighboring pixels.

Four matrices are computed for 0°, 45°, 90°, and 135° describing the transition probability for different directions. The evaluation of these matrices is based essentially on a first order neighborhood (eight nearest neighbors).

The texture-context information is expressed by the matrice of relative frequency $P(i,j)$ with which two neighboring elements separated by a distance d ($d=1$ in our case) occur in the image, one with gray level i and the other with gray level j , in dependence of the angular relationship between the two neighbors.

From these cooccurrence matrices following features can easily be computed :

Angular second moment feature (which is a measure of homogeneity):

$$f1 = \sum_i \sum_j [P(i,j)/R]^2 \quad (9)$$

Contrast feature :

$$f2 = \sum_n n^2 \left\{ \sum_{|i-j|=n} (P(i,j) / R) \right\} \quad (10)$$

Correlation feature (linear dependencies):

$$f3 = \left\{ \sum_i \sum_j [ijP(i,j) / R] - \mu_x \mu_y \right\} / (\text{var}_x \text{var}_y) \quad (11)$$

R = normalization value

$\mu_x, \mu_y, \text{var}_x, \text{var}_y$ means and standard deviations of the marginal distributions associated with $P(i,j)/R$

To obtain rotation invariant features one can compute the first and second statistical moment of each feature for the different directions.

° *Directional Histogram (DH) [18]*

This method is based on a local edge decomposition using a convolution operator called Sobel-mask [27] and computing the gradient of the image in x and in y-direction ($\Delta x, \Delta y$).

For computing the magnitude of the gradient we use the euclidean measure:

$$\| \Delta G \| = \sqrt{\Delta x^2 + \Delta y^2} \quad (12)$$

To take only into account the real edge-like features a threshold t is applied on the magnitude of the gradient such that :

$$\| \Delta G \| \geq t \quad (13)$$

and with L directional classes, where the direction is given by :

$$\Theta = \arctan [\Delta y / \Delta x] + \pi/2 \quad \Theta = 0 \dots \pi \quad (14)$$

the angular class is found by :

$$l = \text{int} [\Theta * L/\pi] \quad (15)$$

the whole normalized directional histogram is represented by :

$$\begin{aligned} H_d(k) &= N\theta(k) / \sum N\theta(l) & k &= 0 \dots L-1 \\ \text{or} \quad H_d(k) &= N\theta(k) / R \end{aligned} \quad (16)$$

where R is the normalization constant

In order to extract rotation invariant features from the parameters of the directional histogram one can compute for example the circular cross-correlation or the second moment of the values represented in the histogram.

The features themselves describe rather well the presence or absence of directional line-like characteristics (probability of directional features) in an medical image (angiography, echography).

° *Gray Level Difference Statistics (GLDS) [17] [19]*

This class of local properties is based on absolute differences between pairs of gray levels, and again sensitive for different directions. for a given displacement $\partial = (\Delta x, \Delta y)$ let

$$f_{\partial}(x,y) = |f(x,y) - f(x+\Delta x, y+\Delta y)| \quad (17)$$

and let p_{∂} be the probability density of $f_{\partial}(x,y)$, so that if m gray levels are present in the image then we have a m -dimensional array, where the i th component gives the probability that $f_{\partial}(x,y) = i$.

Classical features which can be computed of these parameters are contrast, entropy, angular second moment or inverse difference moments for example.

With these directional sensitive features (0° , 45° , 90° , 135°), rotation-invariant features can be computed by taking the two first moments over all directions.

The choice was made on these methods because they are easily computable. But other methods like power spectral analysis, gray level run length statistics or autoregressive models [20] [21] permit also to obtain equivalent texture discrimination.

With ten of the above mentioned features we formed our parametric vector, which is used for clustering and classification purposes.

° *Classification [24]*

For classification needs we used a discriminant analysis [22][23][24][25], giving very interesting results from the point of view of image class discrimination.

The goal of this classification method [25] is to find a transformation from a P -dimensional ($P = 10$ in our case) space $\mathbb{R}^P$ to a smaller M -dimensional ($M = 2$ in our case) space that retains most information of the initial space, or the most discriminant directions, and to obtain a good discrimination between the different classes.

For a given sample set (40 images in our application) one can rapidly obtain an accurate estimate of distribution functions of the different reference classes (image classes) to formulate afterwards very simple decision rules in a dimension reduced space ($M = 2$ in our application).

For this transformation [26] we used the P parameters of the textural features and we made a reduction to 2 factors.

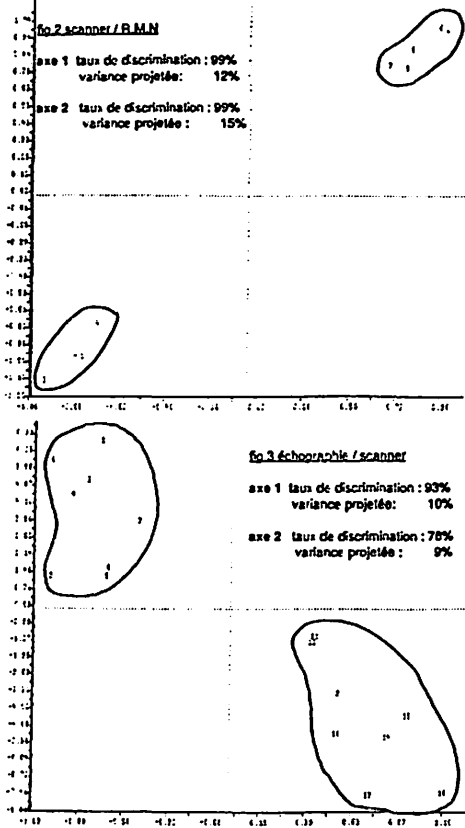
The results obtained with the discriminant analysis turned around 99% for the discrimination ratio with a good projected variance (more than 10% => stability of the clusters) for the different image classes.

Composition of the vector:

- GLDM first and second moment of ASM,CONT,CORRE
- DH second moment and max. of the histogram
- GLDS first and second moment of ENTROPY

Set of images for the learning phase:

40 images (CT, MR, ECHO, DR)



Results of classifications

4. Segmentation of radiological images for compression purposes

By analysing radiological images one can subdivide the image in different contextual regions like :

- anatomic region
- background region
- text region

For this different kinds of regions (after segmentation) it is interesting to apply the best adapted encoding methods, and by this way obtaining a more efficient coding.

Why can this approach be efficient?

By a study which was made with an hospital in Luxemburg, the results show that for certain classes of images (MRI, urographies , thoraxes,...) the background component can take about 30% of the whole image surface.

That means that by an efficient segmentation method [27][28] like *region growing* or a *split and merge* method one can easily fulfill an optimal discrimination between the real image data and the background information, because there exists an a priori knowledge that background is a very low entropy region (specially when impulse noise is eliminated by a median filter for example) and by this way optimizing compression in coding .

Example: An image 1024 x 1024 x 8 bits representing 1 Mbytes of data , for which by using a block-DCT algorithm for [16 x 16] arrays, one can increase the compression ratio from for example 1:10 to 1: 14 by using a one bit flag for distinguishing if the bloc contents background or image information (background arrays are encoded with one bit).

Background and text data (echography) can be very coarsely coded, by simply applying the average gray level for the background region and coding text information after binarization with run-length coding for example.

For anatomic information a system as it was mentioned in the preceding chapter could be used.

An other interesting consideration could be that the radiologist makes with a windowing function a segmentation of the anatomic region, to point out a primary and a secondary region.

The primary region could content the pathological information and so very little or no distorsion can be applied to this region by means of compression (implies a low compression ratio) the secondary region can

be used for topological reference and so a more important compression ratio can be used for this region.

When discussing this point with radiologists it seems that the windowing operation represents a minimum work for them before storing the final diagnostic images.

5. Conclusion

In this paper we first gave a short review of actual used compression algorithms, and we show that specially medical images represent the worst case for image compression at all.

Therefore it is important to use image context and image class dedicated compression to allow an optimal compression with acceptable distortion for the large field of image types which are present in radiology.

The approach which was shown in this paper gives an idea of a possible solution for this kind of dedicated compression.

But a very important requirement will be to construct afterwards the whole system in function of existing compression standards.

In the future a decisive requirement will be to rely on international or de facto industrial compression standards within efficient self-adaptive compression systems.

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TR3: A Simple Multi-Modality Image Handling Environment

Roddy McColl, Tracy Faber, Roger Opperman, et al

Department of Radiology, The University of Texas Southwestern
Medical Center at Dallas, Dallas, TX

Summary

We present a software suite which incorporates a minimal, highly flexible data description with a set of associated manipulation programs and user commands. These may be used in a clinical or research environment in which there is a need for the storage, retrieval and manipulation of data from many original modalities, such as MRI, CT or SPECT. User-derived formats are also easily incorporated, such as Finite-Element Meshes or Colormaps. We have also developed a series of Graphical Applications which operate in an Object-Oriented, or Data-Driven, fashion, in order to make the use of these applications simple for the novice user. The applications typically revolve around the display of some part of an acquisition, which in turn may have been processed with the various software functions prior to display.

1. Introduction

In modern radiology, the clinician and researcher alike face the annoying situation in which various mutually exclusive tasks are required to perform a common operation, the viewing of images from different modalities, such as MRI and SPECT. Growing interest in the registration of multiple-modality studies makes it imperative that a reasonable solution to this dilemma is established. The high cost of multiple hardware platforms is one area in which a multi-modality-display technology could be expected to impact immediately. In order to manipulate, such as display, data from disparate modalities, it is necessary to design a suitable file format, attached as a report to each dataset, which suffices to describe the data therein properly and succinctly. There are a number of researchers and corporate bodies which have developed formats applicable to medical imagery and associated data. We will refer to two of these, the **IMAGE** format and **QSH** software system proposed by Noz and Maguire [1] and the **TIFF** format developed by the Aldus and Microsoft Corporations [2]. In developing the TR3 format, we investigated and compared both of the above approaches.

The file format and software suite described in this paper were developed on computers running the **UNIX**¹ operating system, a common system which is gaining favor in all branches of the computer industry and therefore offers a large degree of hardware independence. The programs will run under BSD 4.3 and System V. With the exception of operating-system dependent programs such as shell scripts, most of the software may be easily modified to run under other common operating systems such as **VMS**². (Another group within the university is developing software using the TR3 file format, running on networked PCs under **MS-DOS**³.)

¹UNIX is a registered trademark of AT&T.

²VMS is a registered trademark of DEC.

³MS-DOS is a registered trademark of Microsoft Corp.

The following section, split into further sub-sections, describes the two parts of the file format, known as the **HEADER** and the **TAG-LIST** respectively, and provides the syntax used in functions which read and write TR3 files. Section 3 describes a typical example of the use of our software suite with data in the TR3 format. The fourth section introduces some graphics applications and explains the data-driven approach taken in designing these applications. Finally, some discussion of the future of this environment, which is still evolving, will hopefully tie up any loose ends in the previous sections.

2. TR3 Header and Tag List

The format we adopted is known as a **tagged** format. This means that the data is partly described through the use of packets of information, found at the end of the file in the case of TR3, which contain data useful for data interaction other than the basic reading, writing and processing tasks which are expected to be the most common. Examples are patient name, physical voxel sizes, etc. The list of tags is always growing, and many are expected to be local to a particular site.

The header is a short packet of information found at the start of the file, which also contains the image data and the tag-list. Rather than choose a scheme such as in the QSH [1], in which the header information is contained in a separate file from the data, and the header file also contains all the tags relating to the data, we decided that, as in the TIFF format [2], the header, data and tags should reside in the same file. The worry of the potential redundancy of the header as the result of loss of the data file, and vice versa, was the main reason for this choice.

We now discuss the header and tags in turn, together with an explanation of the processes involved in opening a TR3 file for reading, writing and closing.

2A. The Header

It was decided that the header should contain only such information as was necessary for the essential operations such as reading, writing and processing the contents of the associated data. There are nine distinct values stored in the header, together with a tenth value which is used to check that the file is indeed in the TR3 format and is not corrupted. The first five values, or fields (as they are known in the syntax of the C programming language) are

n_t ,	the number of entries in increasing time
n_z ,	the number of entries in increasing depth
n_y ,	the number of entries in increasing rows
n_x ,	the number of entries in increasing columns
n_{vals} ,	the number of samples in each entry

so that every dataset is assumed to have the four dimensions (or five if the last field is considered a dimension). In the case of a single image, the first two values would simply be unity. The data are assumed to be in row order. This simple description is surprisingly flexible; an example to which we shall refer later is a dataset in which there are ten gated frames of data, and each entry is in fact the concatenation of co-ordinates in 3-D space and three numbers representing ventricular perfusion, wall motion and wall thickness. This can be represented with the dimensions

[T,Z,Y,X] = [Nframes,1,1,NEntries], [VALS] = 6,

[T,Z,Y,X] = [Nframes,1,NEntries,6], [VALS] = 1,

depending on the preference of the application programmer. The data will be physically in the same order on disk storage in both cases. Conceptually, the former is perhaps more preferable. As a check for validity, the next field in the header is

chk_size, the product of the five dimensions.

At the time a file is opened for reading, if

chk_size **NOT.EQUAL TO** **n_t*n_z*n_y*n_x*n_vals,**

where the asterisk (*) represents multiplication, then we can conclude that this file is not in fact in the TR3 format. This is a more robust check than a popular method in which a Magic Number, some known short sequence of characters of numbers, is placed at the beginning of the file and serves to (hopefully!) uniquely identify the format. Unfortunately, the check we use prevents us from exploiting the UNIX command **file(1)**, which attempts to find Magic Numbers in supplied arguments to the command, and, if found, print a message to the screen, but the multiplication is less prone to circumstance.

The two fields that follow are used to interpret the data in order to define those functions which may meaningfully manipulate the data. The fields are

file_type, the "interpretation" of the data and
data_type, the "interpretation" of each sample in each entry.

Each is a concatenation of several sub-fields which identify particular details. In the case of the **file_type**, the sub-fields identify whether the data should indeed be interpreted as gated or simply a collection of related images, whether the data is grey-scale or in fact a pseudocolor representation (with an accompanying colormap hopefully), or even undisplayable data. One of the sub-fields is used to identify a modality or "type" of the data, which again may be locally defined as needed. In the case of the **data_type**, the sub-fields identify whether the data is signed or unsigned, i.e. whether any of the data are less than zero, and whether the data is in integer or floating-point format, or whether the data is a "string" of characters with terminating symbols or just ASCII data. Simple arithmetic operations may be carried out to select or "mask" those parts of the fields which are not of interest, thus guiding the various functions which are called to process the data in any application. As an example, the function which scales displayable image data to occupy the full dynamic range of the input domain, must decide what the input domain is, and from that which scaling factor to use, in order to meaningfully scale the data.

The final two fields in the file header are

image_addr, the address of the first data point
options_addr, the address of the first tag,

which are used to permit arbitrary data layout. The data is expected to be contiguous, but can be placed starting anywhere in the file. The same scheme applies to the list of tags. These fields permit various functions to quickly find any data or tag.

2B. The Tag List

In practice, it is very unwise to have a file layout other than

HEADER followed by **DATA** followed by **TAGS**

using the TR3 format. The reason for this is that the data itself is unlikely to change. In our system, in fact, processed data is always expected to be written to a new file. The tag-list for image files, on the other hand, is liable to grow as information is attached to the data. If the tags are not at the end of the file, new space must be generated which may involve moving the data "out of the way" to make room for new tags. This is a time-consuming operation for any operating system, so is to be avoided at all costs. The overhead, however, of simply reading in the tags at the end of the file as it is opened for reading, and then writing any new tag-list back in its entirety at file close time, is negligible. In this way, the tags are

saved in a format known as a "linked list" by the application program while the image file is being accessed, and if any new tags are added to the list, or if any tags are modified, the "new" tag-list in its entirety is written to end of the file, starting from the `options_addr` location. The job of finding the extra space at the end of the file is left to the operating system - in general, this process involves a negligible delay. The tags themselves contain three fields, which are

tag_label,	the "name" of the tag, actually an integer constant
data_type,	the "type" of the tag data (as for header above)
nelements,	the number of items of the specified type.

This format is similar to the TIFF tag format. The major difference between TR3 tags and TIFF tags, however, is that in TIFF, the philosophy is to "simply follow the pointers, wherever they may lead" [2] because every tag has a field in it which identifies the starting address of the data for that tag, which may be anywhere in the file. This scheme of course makes expansion of the tag-list straightforward, but makes the file layout complex. As well as this, all file information, including dimension and type definitions, are represented as tags, which makes file processing more involved. A useful advantage of having the file "laid out" in the TR3 format is that it is easy to turn the data back into a "raw" state if necessary (for instance, if the data is to be converted to some unusual format, or if the header information or tags are incorrect).

The overhead of reading in the entire tag-list (and possibly writing it all out again) may seem considerable; in practice, the size of the tag-list is unlikely to exceed a few percent of the data, so the cost of keeping this information online is in fact low.

2C. Reading and Writing TR3 files

The TR3 software is known in UNIX parlance as a "library", and using these routines in a program is known as making "library calls". The library calls used to open and close TR3 format files are arranged in a similar way to the standard UNIX library calls `fopen` and `fclose`. They are in fact functionally almost identical to the calls found in the QSH library, and have the same names. These names were in fact originally part of the University of North Carolina's VSH [3] library. The values returned by the calls reflect the success or failure of the call. For instance, the following lines indicate a call to open a TR3 file in order to read its contents:

```
#include <imagehead.h>
Improg_Header *imphd = imopen("test.img", READ);
```

If this call succeeded, the variable `imphd` would now have all the necessary information about the TR3 file `TEST.IMG`. If the call failed, however, the returned value would be `NULL`, or zero, value, which is returned by the UNIX library call `fopen(3s)` upon error. In addition, the following TR3 call could be used to assess the reason for any open failure:

```
#include <imagehead.h>
int status = imdiag(0);
```

The integer `status` would have a value which would reflect a particular error encountered during the last TR3 file operation, such as a value indicating that the file `test.img` did not exist.

Opening a TR3 file for writing is a more complex operation. It is of paramount importance that the given filename does not exist, otherwise if the user had write permission to the file, it could be truncated to zero length by UNIX at opening time. So the call `imcreat()` must necessarily behave slightly differently to the UNIX system call `creat(2)`. The function checks that the named file does not exist before creating the new file. The following call attempts to open a particular file for writing:

```
#include <imagehead.h>
short filetype = SIMPLE_DATA | SINGLE_IMAGE | GREY_LEVEL;
short datatype = CHAR | UNSIGNED;
long dimensions[5] = { 1, 1, 256, 256, 1 };
Improg_Header *imphd = imcreat("test2.img", DEFAULT, filetype,datatype,dimensions);
```

where the words in uppercase indicate constants. The **DEFAULT** constant allows the owner of the file and other specified users known as the user's group to read and change the file (i.e. it's tag-list) as required. If this call succeeded, the file would be set to contain a single set of data representing a 256 by 256 pixel image, where each entry is one byte in size, and is interpreted as unsigned, in the range [0-255]. Again, if this call failed and returned a NULL value, a call to `imdiag( )` would supply the cause of the failure.

3. Object-Oriented Images

Any display system which makes the display and analysis of images an arduous task for the clinician is unlikely to be popular. Many hospitals purchase computer systems which subsequently are rarely used because of the sheer effort required to use them effectively. It is important that in any user-oriented application, the choices available are understandable and are the only choices which can be made given the present data. For instance, the option to display the 3-D-coordinates/ventricular-parameters example discussed in the previous section is meaningless and would be confusing if it were offered. The applications developed for use with **TR3**-format data have been expressly designed to allow only options which are meaningful at that moment, to reduce confusion as far as possible. The applications included allow the user to

- A) extract a 4-D subvolume from an acquisition
- B) interactively segment parts of interest in a 4-D set
- C) cine gated sequences
- D) make physical measurements on displayable sections
- E) overlay MRI images with SPECT for registration
- F) construct and display wireframes from MRI and SPECT.

In each of these applications, the emphasis has been that the user can only apply those functions which are meaningful at that time. In the wireframe rendering application, the user could select as input any file with 3-D-coordinate/ventricular-parameters data, but would not be able to "find" i.e. see, choices which contained e.g. MRI data.

The particular environment we have worked under is the **SunView**⁴ window system. With the rapid rise in popularity of the **X**⁵ window system, under which we are also developing software, a largely hardware-independent windowing environment, is available in which to run simple-to-use medical imaging applications supporting multi-modality data.

4. Conclusions

We have presented a brief description of the **TR3** image file format and software environment. The emphasis in the development of **TR3** has been

1. Simple, extensible image descriptions
2. Data-driven user applications.

⁴SunView is a trademark of Sun Microsystems Inc.

⁵X is a trademark of Massachusetts Institute of Technology.

It is hoped that these goals have been properly explained in this paper. We believe they have been met in general with TR3. The library, and some of the key concepts, are still fluid however, as certain factors become of temporary importance to users and programmers. The commands available to the user grow but it must be borne in mind that an overly-rich environment will tend to cause confusion, so the list is limited as far as possible. The software has been tested on computers from Sun, Stardent and IBM. There is support for conversion to and from a number of other formats, including TIFF. Further descriptions of application software will be presented at a future date.

Acknowledgements

We wish to thank Drs. Noz and Maguire for providing us with QSH software which provided the initial impetus for our work on TR3.

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Image Processing

General Session

A Comparison of Surface and Volume Rendering Methods

Jayaram K. Udupa and Hsiu-Mei Hung

Medical Image Processing Group, Department of Radiology,
University of Pennsylvania, Philadelphia, PA

Abstract

This paper compares a particular surface rendering method with a specific volume rendering technique. The former has not been published in the literature and hence is described in some detail. The latter constitutes a published work and the comparison is based on our own implementation of this work as close to its original form as possible. The bases of comparison are: ability to portray thin bones, clarity of portrayal of sutures, fractures, fine textures, and gyrations, smoothness of natural ridges and silhouettes, and time and storage requirements. Our preliminary conclusion is that the surface method has a slight edge over the volume method for the portrayal of information of the type described above and a significant advantage as far as time and storage requirements are concerned, for implementations in identical environments.

Introduction

Currently there are two classes of approaches, known as surface rendering and volume rendering, available for visualizing and analyzing medical three-dimensional images. In surface rendering, the premise is that the given image contains data pertaining to certain tangible structures in the human body, and hence, that each structure can be visualized by its surface estimated from the image. In volume rendering, there is no assumption of an underlying structure or its surface, rather the tissue material of each structure to be visualized is estimated in every voxel and the structures are visualized through radiosity calculations based on the opacities and colors assigned to different tissues and on some assumed optical behavior of tissues. In both methodologies, the important issue is how to do rendering so that medically *relevant* information is portrayed in the rendered image.

Recently there has been a spurt of activity related to volume rendering and its medical applications. Many claims of superiority of volume over surface rendering have also been made the validity of which is neither obvious to us nor has been established scientifically. Unfortunately, some claims have been accepted as established facts and have started appearing in the standard literature. The comparative assessment of surface and volume methods is a very complex subject. It is not possible to derive scientific facts on this subject independent of the organ system under study, the imaging modality and its parameters, the actual application, the algorithms used in each methodology and their parameters, and the observer. The scope of our study is, by necessity, limited, but hopefully it will initiate further studies of this nature on this important subject.

For surface rendering, the methodology used is our own [1], and for volume rendering, we use the technique reported in [2]. Since the main objective of this paper is comparing the methods, we will not delve into their description. Our comparison is based on our implementation of the methods in a common computing environment.

Comparison

We use two data sets for comparing the renditions created by the two methods. The first is a $512 \times 512 \times 62$ scene pertaining to a trauma victim obtained via CT with a uniform pixel size of 0.4 mm and a slice spacing of 1.5 mm. The structure of interest here is the patient's skull. The second data set is a $256 \times 256 \times 32$ scene of a human brain specimen obtained via MRI. The pixel size and slice spacing for this data are 0.78 mm and 3 mm. In creating renditions, we have used identical values for the two methods for the parameters that are common to the two methods. All images are created without any antialiasing. We have used three different "resolutions" for the rendered images. For *medium resolution*, we assume that the voxel size a_I for the interpolated scene is equal to the pixel size a_R in the input scene. For *high resolution*, we assume that $a_I = \frac{1}{2} a_R$ and for *low resolution* $a_I = 2a_R$. For all resolutions and for both methods, the size of the two-dimensional array defining the image is determined such that the projection of a single boundary face for any orientation of the object of interest falls just inside a single pixel of the image.

In an attempt to determining what should be the optimal values for the parameters of the classification function used in volume rendering, we have created literally hundreds of images corresponding to some chosen view of the structure by varying the values of the parameters continuously over an interval whose end points in our view represented extreme situations. We do not claim that our choice of values for these parameters is the best possible, yet this arduousness signals a difficulty which indeed is a counterpart of the difficulty of segmentation in surface rendering.

Figures 1-4 show some renditions derived from the two scene data sets described earlier. Figures 1 and 2 show identical views generated from the first data set by (a) the surface and (b) volume methods at medium (Figure 1) and low (Figure 2) resolution. Figure 3 shows identical views generated from the second data set by the two methods at high resolution. Our following comparative statements are based on these and other images we have generated and on our experience with the two specific implementations of these methods. We emphasize that there was no interactive editing of any sort involved in the creation of any of these images.

Thin Bones: Depiction of thin bones, especially those in the vicinity of the orbits, is equally poor in the two methods. There are two main reasons for this difficulty. First, the characteristics of the scene in the vicinity of thin bones are very similar to those of the skin. Therefore, except when dry skull specimens are used, it is just about impossible to segment for surface rendering or classify for volume rendering voxels constituting thin bone differently from those constituting skin using global criteria such as those used in this paper. More sophisticated neighborhood operators have been studied [3] for segmenting such voxels with some success in scenes of lower resolution than that used here. In our implementation of this technique, the improvement achieved was negligible, perhaps because the neighborhood characteristics responsible for the earlier success are no longer valid in the higher resolution scene. The second reason is that even when thin bones can be segmented/classified effectively

(say using some specialized knowledge), their effective rendering is difficult because the normal N computed from an estimate of the gradient in the vicinity of thin bones is not reliable. In fact, when we modified the surface rendering algorithm to incorporate some specialized knowledge such as specifying the approximate region in which thin bones may lie and to use features in addition to density, we were constantly misled by the rendering because of unreliable N . Only when we resorted to distance-only shading, we saw the improvement in the detection of thin bones resulting from the modified algorithm. These problems constitute important research topics in both surface and volume methods.

Sutures, Fractures, Fine Textures: There is no clear advantage in either of the methods for the depiction of these features. In our view, the surface method produces sharper depiction of the features than the volume method.

There is a certain amount of tolerance and robustness in the surface method used here which are responsible for the effectiveness of the depiction of fine features irrespective of the digital nature of the surface. For example, for a suture of a skull to be portrayed effectively, it is not necessary that the feature be modelled precisely in the digital geometry of the surface. All that is required is that the feature be in the close vicinity of the modelled surface. Appropriate interpolation and normal estimation procedures guided by the geometry of the surface can bring out the feature in the rendition. In fact, the rendition using even a thresholding method is surprisingly insensitive to the actual threshold used. Figure 4 shows a surface detected at a threshold value 60 Hounsfield Units above that used for the surface shown in Figure 1(a).

Gyrations, Ridges, Silhouettes: The silhouettes and natural edges appear to be portrayed smoother by the surface method than the volume technique. Though the underlying surface geometry is digital and hence jagged, because of the method of estimating N and of determining the real (rather than digital) location of boundary faces [1], the display of ridges and edges does not show jaggedness even without the antialiasing operation. The gyrations of the brain surface are portrayed equally well by the two methods. In general, the surface method seems to show the 'slicing artifact' more prominently than the volume method, perhaps mainly because, in the latter, such artifacts are smoothed out by the integration process. This phenomenon, in our view, has an undesirable effect namely that subtle natural textures in the surface are portrayed poorly in the latter method (See Figure 1).

Time and Storage: It is not possible to give a precise comparison of speed of rendering for the two methods since our implementation of the volume method is much less optimized compared to the surface method. Two orders of magnitude speed up over a straightforward implementation has been achieved for the volume method [4] using a variety of techniques whose objective is to minimize the number of rays cast and the number of voxels sampled along each ray without sacrificing image quality. Based on the reported timings, our estimate is that, for the current state of optimization for the two methods and implementation in an identical environment, the surface technique is 25-30 times faster than the volume method. The number of surface elements (1.2 million for the example of Figure 1(a)) is usually much smaller than the total number of voxels that enter into computation in volume rendering. Further, the actual computations done per element during rendering are fewer and simpler in the former method than in the latter. In our implementation, the preprocessing time required by the former method is roughly 1/3 that required by the latter.

The storage requirement during the rendering process is determined mainly by how the algorithms are implemented. In general, as the implementation is made more and more optimal for speed, the memory requirement increases and vice versa. The volume method requires enough space to store two scenes in addition to the space required to store the image being generated. The surface method requires random access only to an image and a z -buffer and not to the surface data, and therefore the memory required is determined by the size of these buffers. With these considerations, the CPU memory required during rendering by the surface method for the example in Figure 1 is about 20 times less than that required by the volume method, though this factor for disk space requirement is about 3-4.

Finally, in our experience, the volume method is easier for a straightforward first implementation than the surface method.

Conclusions

From purely a technical viewpoint, we consider that the surface rendering method of the type described in [1] should be preferable to the volume method considered in this paper [2] on the basis of the nature of the information portrayed in the renditions and time and storage considerations. As we tried to improve our implementation of the two methods it became clear to us that the differences between them start disappearing. Therefore it is just as relevant to compare between these methods as it is to compare techniques in the same methodology. In our view, the sources of the shortcomings in the two methodologies are common. There is a great deal to be benefited by each methodology from developments in the other since a new development in one has often an appropriate parallel connotation in the other. For example, it is possible to combine some of the ideas related to normal estimation and interpolation used in surface rendering with the volume rendering method. We could have done even a connectivity analysis to discard the clutter appearing in the volume rendition examples. Then the differences between the two methodologies start disappearing and only their common weaknesses remain. The bottom line, in our view, that decides which methodology is superior in a particular visualization task is which is more effective, segmentation or classification, in successively identifying tissue regions and interfaces. If situations exist where there is such a difference, the design of appropriate techniques that yield the difference is an interesting research topic.

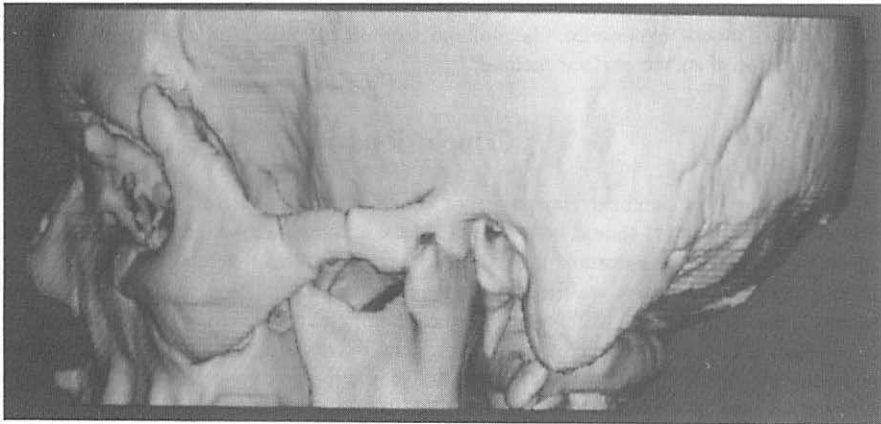
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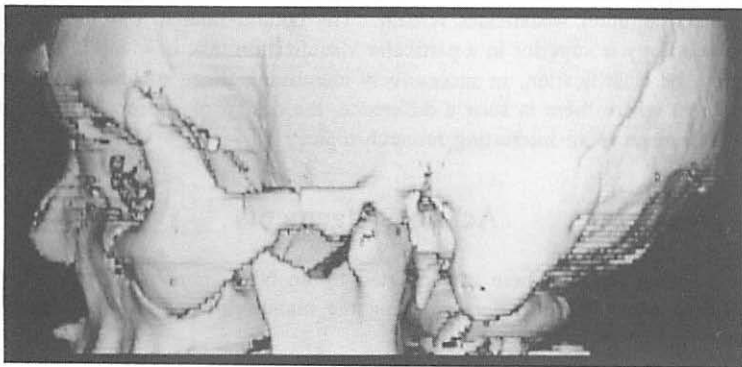
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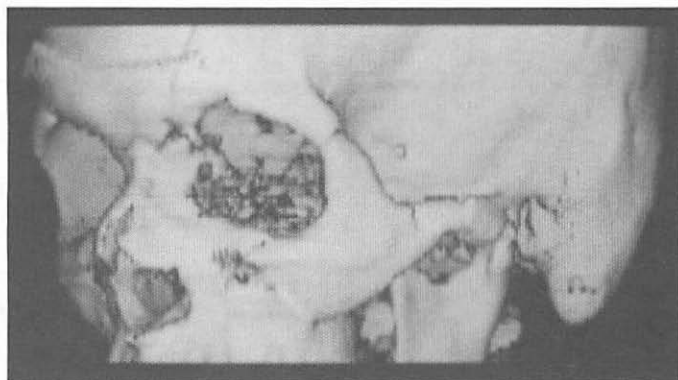


a

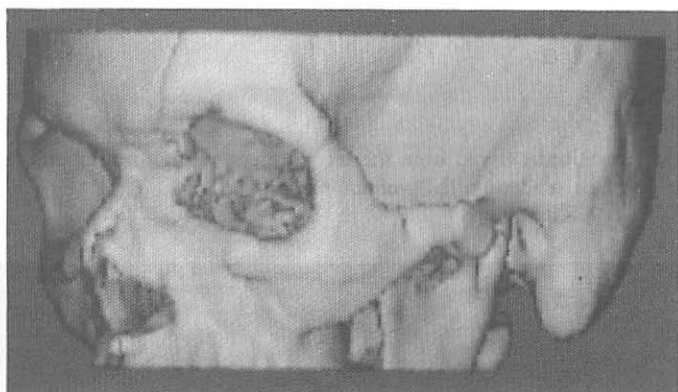


b

Figure 1. Renditions derived from the first scene at medium resolution: (a) surface rendering, (b) volume rendering.



a



b

Figure 2. Renditions as in Figure 1 but computed at low resolution and different views.

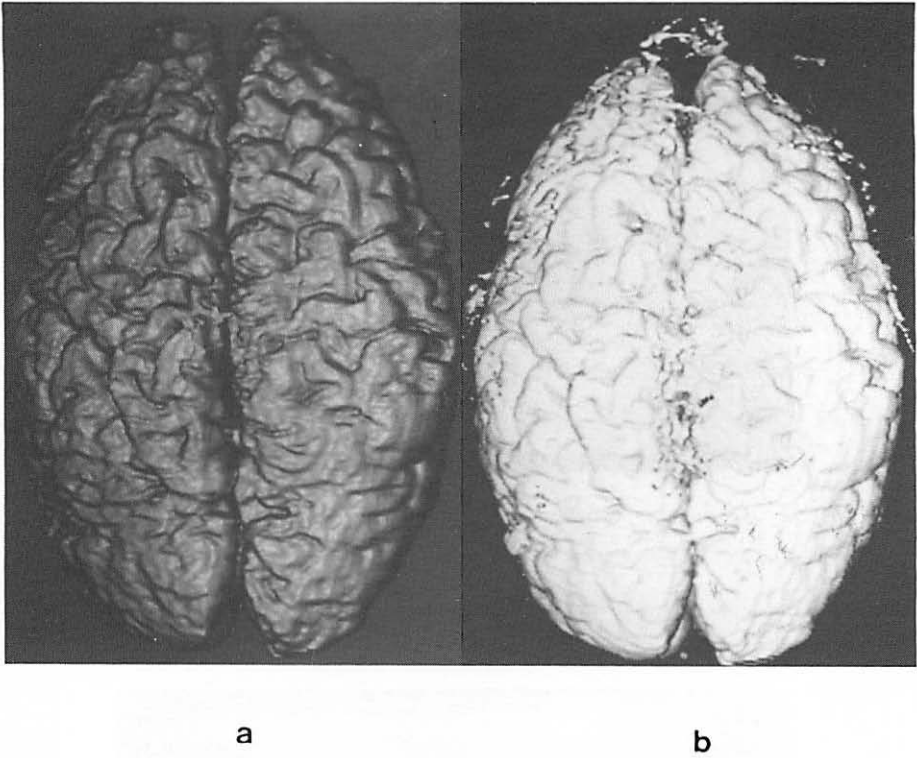


Figure 3. Renditions derived from the second scene at high resolution: (a) surface rendering, (b) volume rendering.

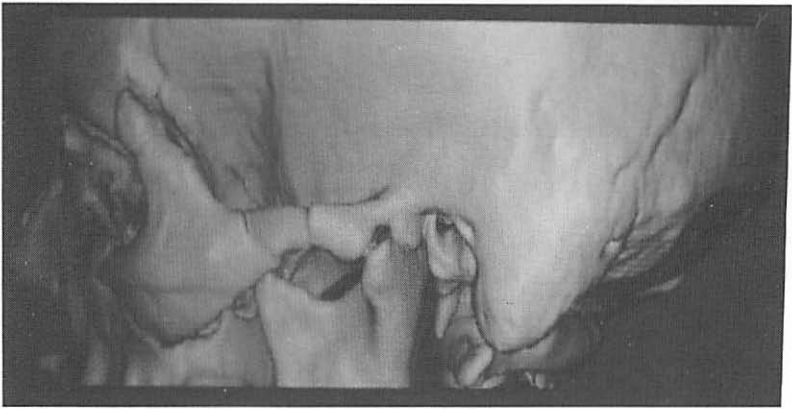


Figure 4. Surface rendition as in Figure 1(a) except for 60 HU higher threshold.

Image Features of Mammographic Masses Used in the Development of Computerized Schemes

Maryellen L. Giger, F.-F. Yin, K. Doi, et al

Kurt Rossmann Laboratories for Radiologic Image Research,
Department of Radiology, University of Chicago, Chicago, IL

work in progress

Introduction

Due to the effectiveness of mammographic screening in the reduction of mortality from breast cancer^{1,2}, we are investigating various radiographic features of the typical mammographic examination. Our principal efforts have been towards the development of schemes that aid radiologists in the detection of breast cancer. This paper reviews two radiographic features of masses that radiologists use in the detection of breast cancer: the expected architectural symmetry of the left and right breast images of the same view (e.g., cranio-caudal or medio-lateral-oblique) and the presence of spiculation along the mass margin.

The analysis of architectural symmetry between the left and right breasts has been adapted by radiologists as a useful tool in detecting masses in mammograms³. Radiologists are taught to visually compare corresponding parts of the left and right mammograms in order to inspect isolated selected regions for possible abnormalities³. Our computerized detection scheme is motivated by this systematic method of viewing mammograms.

In current clinical practice, after a mass is found by a radiologist, a subjective likelihood of malignancy is determined by visual inspection of the mammogram. One of the primary radiologic features used in differentiating malignant and benign masses is the amount of spiculation of the mass. Our computerized scheme attempts to quantify the degree of spiculation of detected masses in order to aid in their classification.

Methods

We are developing a nonlinear bilateral subtraction technique for the computerized detection of masses in screening mammograms. In this scheme, gray-level thresholding is performed on corresponding digital images of the left and right breasts prior to digital subtraction using a "left-minus-right" convention. After subtracted pairs of various threshold images are obtained, the resulting data are combined into two images that contain information regarding suspicious areas in both breasts. Feature-extraction techniques are then applied to reduce the number of false-positive detections.

Our computerized scheme for the classification of detected masses measures the amount of spiculation exhibited by the mass in question. First, the mass is extracted from the anatomic background of the mammogram. In this study, the extraction procedure was performed either by having a radiologist manually outline the mass or by having the computer track the border from a binary image obtained using gray-level region growing. Spiculation can be considered a fluctuation about the border of a mass. After a mass is isolated from the background, its margin is smoothed in order to substantially reduce possible spicules. The difference before and after the smoothing operation provides an indicator of the magnitude of fluctuations, with a large difference corresponding to a high degree of spiculation and therefore, a greatly increased likelihood of malignancy. Two measures of spiculation are the standard deviation of the fluctuations about the mass border, and the normalized difference in the areas of the mass with and without the presence of spicules.

Results

The detection scheme was examined using 46 pairs of clinical mammograms (18 patients with a mass and 5 patients without a mass). The screen/film mammograms were digitized with a TV camera/Gould digitizer yielding a 512 by 512 by 8-bit image matrix with an effective pixel size of 0.4 mm. The presence of masses in the images had been verified by surgical biopsy. This preliminary study yielded a true-

positive detection rate of approximately 95% with 3 false-positive detections per image on average.

The scheme for quantitation of spiculation was examined using 35 mammographic masses. The pathology (malignant or benign) of each mass had been determined from surgical biopsy. Screen/film mammograms were digitized using an optical drum scanner with a 0.1 mm pixel size and 10-bit quantization. The spiculation measures obtained using hand-drawn outlines correlated well with those obtained from the computer-determined outlines. Also, the calculated measures of spiculation agreed well with a radiologist's subjective impression of the degree of spiculation exhibited by the masses.

Our preliminary results suggest that computerized detection and classification schemes may aid radiologists as a diagnostic tool.

Acknowledgments

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Quantitation of Instantaneous Blood Flow Rates From Angiograms Using Distance-Density Curves

Kenneth R. Hoffmann, Kunio Doi, R. Ramsey, et al

Kurt Rossmann Laboratories for Radiologic Image Research,
Department of Radiology, University of Chicago, Chicago, IL

I. INTRODUCTION

Quantitative analysis of angiograms, two-dimensional images of the vascular system formed by the projection of x rays through blood vessels into which an iodine contrast agent is being injected, may provide useful morphologic and functional information on the vascular system for the diagnosis of vascular diseases. Computerized methods have been developed for quantitative measurement of vessel sizes in angiograms.¹⁻⁶ However, neither absolute vessel size nor percent stenosis directly reveals the functional significance of stenosis, i.e., its effect on blood flow. Thus, measurement of flow rates would be useful for evaluation of the significance of stenosis. In addition, flow rates could be employed to determine coronary flow reserve and to evaluate the effect of interventional procedures.

Several investigators⁷⁻¹¹ have proposed methods for the determination of blood flow rates from angiograms. The flow rates were calculated from the vessel cross-sectional area and the velocity of the bolus which was estimated using the time required for the bolus to traverse the distance between two locations in the vessel, i.e., the time of transit. The time of transit was estimated as the difference between time parameters calculated from time-density curves which were obtained at specified locations in the vessel. Time-density curves represent the concentration of contrast material at a given location in the vessel as a function of time. For steady-flow conditions, average flow rates have been calculated to within 5% of the true flow rates.^{8,11} However, for pulsatile-flow conditions, such as those in arterial flow, the average flow rates calculated from time-density curves have been found to deviate from the true average flow rates by as much as 100%, and the average error in the calculated flow rates is approximately 20%.^{7-9,11}

In this study, we present a new method for determination of blood flow rates from angiograms which is based on analysis of the temporal dependence of the spatial shift of the contrast material in opacified vessels in angiograms acquired as the bolus of contrast material proceeds through the vessel. In our method, time-density curves are not employed, rather the flow rates are calculated from distances determined by comparison of curves (which will be called distance-density curves)

which represent the concentration of contrast material as a function of distance in the vessel.

II. MATERIALS AND METHODS

Digital images of a vessel phantom were obtained using a Digitron 2 DSA system with a matrix size of 512x512 and a pixel size of 0.36 mm.¹¹ The image data from the Digitron 2 were analyzed with a VAX 11/750 computer connected to a Gould-DeAnza FD5000 image processor and CRT display. The vessel phantom consisted of non-distensible tygon tubing with a 6.7 mm nominal inner diameter oriented parallel to the imaging plane of the image intensifier. The phantom was imaged with a 9 cm thick lucite plate in order to generate scatter similar to that of the body. A pulsatile pump was used for supply of a 0.9% normal saline solution through the phantom. The pulsatile frequency of the pump was maintained at approximately 1 Hz, and experiments were performed for average flow rates ranging from 3.5 to 10 cc/sec. Instantaneous as well as average flow rates were measured with a 6.7 mm extracorporeal flow probe and a Cliniflow electromagnetic flowmeter equipped with a strip chart recorder. Images were acquired at 15 frames/sec as an injection of 2 cc of Renographin was delivered with an Angiomat 3000 injector over 0.25 to 0.5 sec at a distance of approximately one meter from the imaged section of the vessel.

After digital subtraction, a vessel region was manually selected for analysis, and the centerline of the vessel was determined. The vessel size and contrast were determined along the length of the vessel. The cross-sectional area of the vessel was estimated from the vessel size by assuming a circular cross section for the vessel. The vessel contrast was determined as the difference between the average pixel value in the central region of the vessel and the average pixel value in the adjacent background region. From the vessel size and contrast, the distance-density curve was calculated for each angiogram. We found that the shape of the distance-density curves remains fairly constant over short time intervals as the bolus proceeds along the vessel. Thus, the distance that the bolus moves along the vessel between two image acquisitions can be determined by comparing the respective distance-density curves. It should be noted that the shapes of the time-density curves have been observed to change as a function of distance along the vessel.^{7,12} The distance-density curves were compared by shifting one of the curves spatially in an iterative manner until the root-mean-square difference between the curves was minimized. The spatial shift which yielded the minimum root-mean-square difference was considered to be the distance that the bolus traversed between the two acquisitions. The "average" flow rates between the acquisitions were then calculated from this distance, the frame rate, and the cross-sectional area of the vessel. Thus, for high frame rate acquisitions, "instantaneous" blood flow rates can be determined.

III. RESULTS

Figure 1 shows the instantaneous flow rates (circles) calculated using the distance-density technique from a study in which the average flow rate was 5.0 cc/sec. For comparison, the instantaneous flow rates measured by an electromagnetic flow meter are plotted here as the solid line. For the fourth pulse and the first portion of the fifth pulse, the "instantaneous" flow rates calculated from the distance-density curves appear to agree well with those measured by the electromagnetic flow meter. For the second pulse, the apparent disagreement between the flow rates obtained with the two techniques may be due to laminar flow effects and saturation effects. In the case of laminar flow, the flow rate in the center of a vessel is twice the average flow rate across the vessel lumen. It should be noted that, for the first portion of the second pulse, the calculated peak flow rate is approximately twice the peak rate measured with the electromagnetic flow meter. Thus, these results indicate that the calculated flow rates may correspond to those in the central region of the vessel lumen. The flow rates during the time between 1.0 to 2.2 seconds were probably underestimated because the vessel was at maximum opacification for this phase, and thus, the corresponding distance-density curves were nearly saturated.

For the studies performed, we have determined that the instantaneous flow rates measured with our technique agreed with those measured with an electromagnetic method to within an average of 2.3 cc/sec for pulsatile flow conditions with peak flow rates of up to 20 cc/sec. In addition, the average flow rates were calculated from the slope of the straight line which best fit the curve representing the cumulative distance traversed by the bolus as a function of time. The average flow rates determined using the distance-density and electromagnetic methods agree to within an average of 11% with a maximum deviation of 28%.

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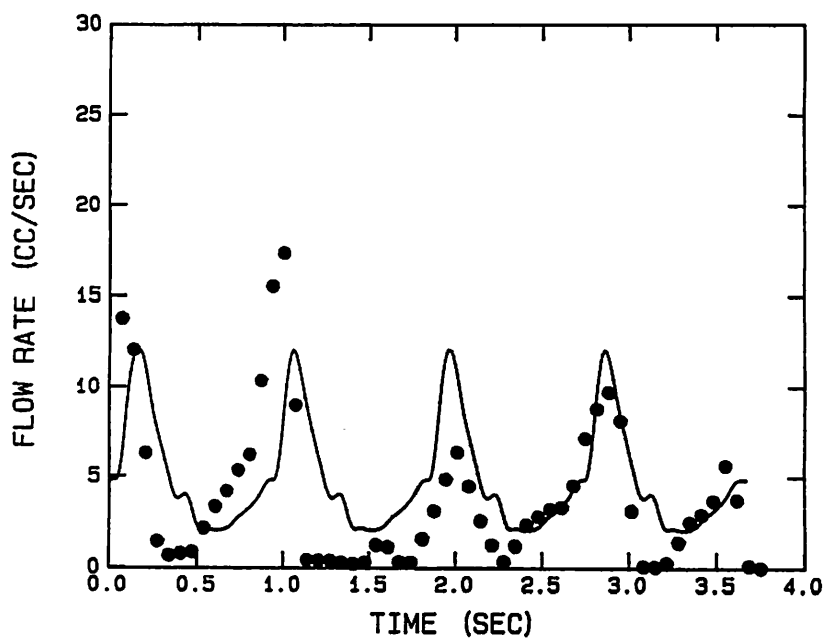


Figure. 1. Comparison of the instantaneous flow rates calculated from the distance-density curves (●) and those measured with an electromagnetic flow meter (solid line). The average flow rate was 5.0 cc/sec.

Computer-Assisted 3-D Reconstruction and Interactive Manufacturing of Alloplastic Cranial and Maxillofacial Implants

H.-J. Schmitz

Clinic for Maxillofacial and Facial Plastic Surgery

T. Tolxdorff and J. Honsbrok

Institute for Medical Statistics and Documentation

A. Harders, G. LaBorde and J. Gilsbach

Clinic for Neurosurgery, Medical Faculty,
RWTH Aachen, Aachen, WEST GERMANY

Summary:

In a series of 16 cases 3D-models after matching their overall dimensions and structural details to actual anatomical measures were used for surgical planning and simulation as well as predominantly for fabrication of large individual alloplastic implants for cranioplasty. The model mediated implant manufacturing finds increasingly more indications with far better overall results in aesthetics and quality of cranioplasty, since models in true dimensions can be made available in short reconstruction and milling intervals of about one week.

Introduction:

Preliminary experience on 3D-based computer assisted manufacturing of individual alloplastic implants for cranial and maxillofacial osteoplasties has already been presented on the CAR'89 meeting in Berlin [7]. 3D-imaging is becoming increasingly successful in clinical applications. VANNIER et al. [8] demonstrated that premature synostoses were more easily diagnosed by use of 3D-imaging, while normal x-ray was equally effective in detection of pelvic fractures. Knee injury diagnostics have been improved by three dimensional display of mathematically disarticulated objects [4]. In orthopedics CAPS - computer assisted prostheses selection - is being applied to facilitate the right choice of hip endoprotheses selection [1] and in surgery of cleft palate and cranial deformities MARSH and VANNIER already some years ago pointed out the usefulness of 3D-techniques for surgical planning [6], which was recently improved by sophisticated 3D-disarticulation methods [11]. TOENNIES et al. [9] demonstrated the use of surface registration for the segmentation of implanted bone grafts.

ULLRICH and MATHEWS assessed the use of 3D-CT in 100 cases of facial fractures [10] and Craniofacial applications were evaluated recently by McEWAN et al. [2].

However, the rendering of 3D-images for surgical planning and diagnosis in most image processing systems like CEMAX, PIXAR, KONTRON etc. does not display 1:1 real size 3D-images, thus making calculation of conversion multipliers necessary. Despite fabrication of 3D-alloplastic individual implants pose little technological problems, at least since the feasibility was proven years ago, there was no decisive increase in application of this technique. The professional application has been restricted to some singular cases due to problems of matching visualization and 3D-milling and to guarantee real size implants. Most of all due to a lot of detail problems which are often more or less organizational and coordinational difficulties. In principle two methods are known:

- direct implant milling right after designing in a CAD system,
- indirect, model mediated 3D-implant generation.

In the mean time the number of clinical applications and indications has increased.

Methods:

CT data were generated on CAT scanners SIEMENS SOMATOM-II or -DRH with 256x256 or 512x512 matrices. Five second slices were recorded at 1 or 2 mm intervals. Data were stored in compressed mode, single density, on 8 inch floppy disks. The disks were sent to HOWMEDICA GmbH, Kiel, Germany, for reconstruction and milling of models.

To reconstruct bony defects the CT image data were segmented by threshold methods based on Hounsfield units. For thresholding a suitable interval was selected. The image matrices were transformed in binary matrices according to this Hounsfield interval representing the bony structures of interest.

The contour of the bone structures were detected by a recursive algorithm. The algorithm first traces the boundary, then the inside of the boundary to detect holes using the dualism of inner and outer contours. In particular the algorithm builds a data-structure (contour tree), which reflects the appearance of holes and branches.

The geometrical model of the bone structure was generated by matching the contour tree elements obtained from adjacent slices. This surface of the bone structures was reconstructed out of two matched contours under the constraint,

that the surface of the model was minimized (CHRISTIANSEN et al. [3], FUCHS et al. [5]).

Using the MEK-system (MEK: Medizin-Elektronik GmbH, Kiel, Germany), a life sized 1:1 polystyrene or polyurethane model was prepared by a 5 axle milling machine.

Results:

In the original setup a segmentation of bony contours was done with a Hounsfield value of 190. These parameters, however, did not represent patients true bone stock, rather overestimating skull thickness by 20-30%. By comparison of fresh anatomical skull specimens dimensions with those of the milled models, a standardization of the method was achieved to give a close matching of overall model sizes and detail skull thickness to actual patients dimensions. Finally two different Hounsfield parameters were used to describe the outer and the inner skull cortex borders.

A.: Planning of surgical procedures was done in polyurethane models in:

- mandibular hypoplasia,
- facial skoliosis,
- posttraumatic facial asymmetry,
- Apert syndrome,
- hypertelorism and craniofacial stenosis,
- carcinoma of floor of mouth infiltrating skull base in middle cranial fossa.

Planning of surgery with help of models was rated very successful - the model providing considerable help to the surgeon in preshaping of contours, determination of osteotomy sites allowed for improved surgical results.

B.: Preoperative simulation of tumor surgery was done in:

- meningioma en plaque of the left sphenoid wing, (C. R.)
- meningioma of the right sphenoid. (D. R.)

Preoperatively the tumor masses were excised in the models; the respective defects were pre-Op closed by wax modellations according to the unaltered contralateral structures. Wax modellations were converted into polymethylmethacrylate (PMMA) bone cement implants or into the new IONOS^R glass-ionomer bone cement implants using impression techniques.

Pre-Op TU excision was simple in the case of very clear tumor borders in C.R. (Fig.1). Though the defects contours created in the model did not match the

definitive osteotomy size, an intraoperative shaping of the prefabricated glassionomer implant was easy. The implant was glued into the left temporal defect thus reconstructing subtemporal and temporal bone and lateral orbital wall (Fig.2). In the D.R. case with more diffuse TU-infiltration of sphenoid wing, orbital roof up to the optic canal, and the sphenoid sinus delineation of TU-borders and preoperative definition of extent of bone excision proved more difficult. A glassionomer implant replacing subtemporal bone and part of lateral orbit was prefabricated. Intraoperative reshaping of the implant to a small extent and adjustment to the craniotomy defect were necessary, the skull-implant was then glued into the defect reducing general operation time considerably.

C.: Alloplastic cranioplasties were performed in the following cases:

- left frontoparietal, (L. V.)
- bifrontal, medial, (L. I.)
- bifrontal, medial, (M. H.)
- right fronto-orbito-parietal, (E. C.)
- right parietal, over midline, (W. R.)
- bifrontal, medial, (B. H.)
- huge, bifronto-biparietal. (L. T.)

Implants were molded and skulptured in wax according to symmetry and with regard to preoperative patients appearance. Using plaster of Paris molds and impressions were made and wax specimens converted into implantable bonecement skulls using PMMA or IONOS^R glassionomer cement, either. PMMA-specimen were sterilized by immersion in polyiodine solutions for 48 hours, IONOS^R glassionomer-cement specimen were sterilized by autoclaving.

Skull reconstructions were extremely improved using 3D-prefabricated implants of either IONOS^R glassionomer cement or PMMA. Frontal-parietal and temporo-lateral aspects were nicely contoured to general skull symmetry. Especially difficult fronto-orbito-parietal reconstruction, including supraorbital rim, part of the orbital roof and continuity to fronto-zygomatocal process of zygoma were reconstructed to a high degree of standard and craftsmanship. Fixation of alloplastic implants was accomplished by either suturing or using the adhesive properties of the new IONOS^R glassionomer cement, which in tensile testing exhibited an interfacial tensile strenght of 1 - 2 N/mm². So far no complications, e.g. no infections, were encountered in the present series.

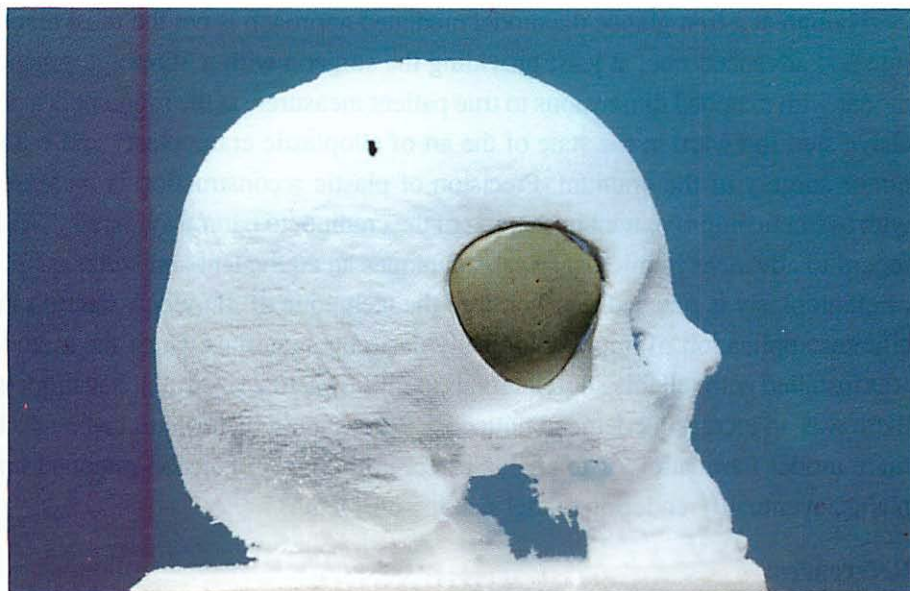


Fig.1.: 3D-reconstruction, polystyrene model after excision of meningioma en plaque and closure of defect by molded alloplastic implant.

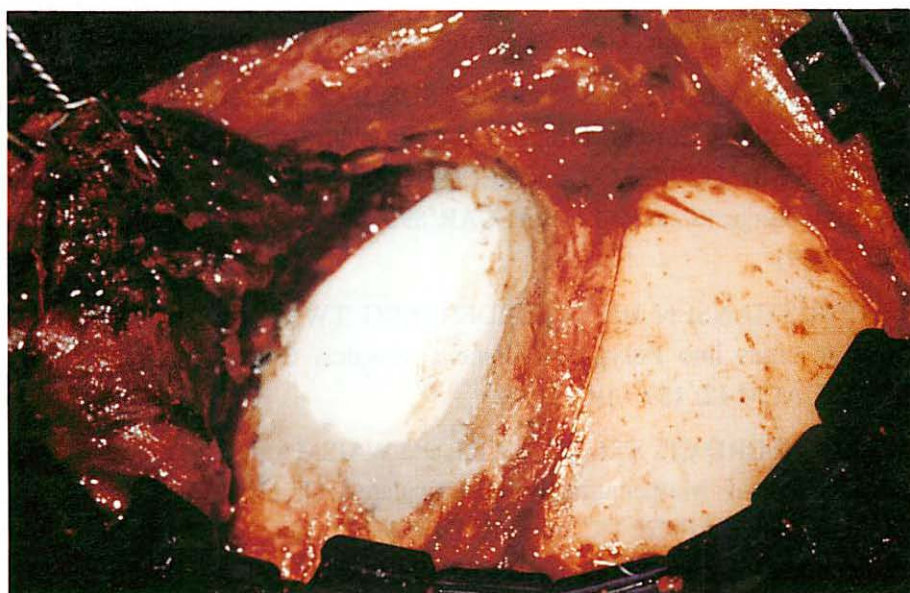


Fig. 2.: Fitting of individual IONOS^R glassionomer 3D-implant in temporal craniotomy defect. The implant is glued into the defect.

Conclusion:

Though at a first glance the model mediated approach is not the most elaborate and advanced one, at least providing the surgeon with a 3D-polyurethane-model with matched dimensions to true patient measures, at the moment is a decisive step forward in the state of the art of alloplastic cranioplasty and bone-tumor surgery of the cranium. Precision of plastic reconstruction is increased with aesthetic improvement in shaping of the cranium to natural symmetry. With regard to advances in microsurgical techniques an equivalent and better quality of cranioplasty is reached. Furthermore the technique of 3D-reconstruction facilitates application of implantologically desirable materials. Once the method was installed with reliably short intervals of milling actual sized matched models, there was an increasing demand noticed. Efforts should be made to further facilitate model fabrication or to enable direct milling of dimension-matched implants, eventually rendering model-making obsolete.

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Graphics and Image Enhancement

Spatially Resolved Characterization of Incoherent Flow Fields by Nuclear Magnetic Resonance Imaging

O. Nalcioglu

Department of Radiological Sciences, Division of Physics and Engineering, University of California, Irvine, Orange, CA

1. Introduction

Fluid mechanics is one of the fields that branches out into various specialities all the way from aerodynamics to medicine. It deals with the statics, kinematics, and dynamics of fluids, since the motion of a fluid is caused by unbalanced forces exerted upon it. In this paper, we will be concerned with some of the dynamic properties of liquids. The static properties of fluids will not be dealt with. We will describe a flowing liquid by a flow field. The mathematical description of the state of a moving fluid is effected by means of its velocity $\mathbf{v} = \mathbf{v}(x,y,z;t)$, the pressure $p(x,y,z;t)$ and the density $\rho(x,y,z;t)$. If we are given the three components of the velocity $\mathbf{v}$, the pressure p and the density ρ , the state of the moving liquid is completely determined. It should be remembered that all the qualities are, in general, functions of the coordinates x,y,z and of the time t . We emphasize that $\mathbf{v}(x,y,z;t)$ is the velocity of the liquid at a given point (x,y,z) in space and at a given time t , i.e., it refers to fixed points in space. The same remarks apply to p and ρ . In this paper, the spatially resolved characterization of a flow field will mean the measurement of $\mathbf{v}$ as a function of (x,y,z) and t . Once the velocity field is known, the pressure field could be determined from it by employing the Navier-Stokes equation [1]. A technique for measuring the pressure variable $p(x,y,z)$ was described in ref. [2].

The earliest work towards the noninvasive measurement of flow by nuclear magnetic resonance (NMR) *in vivo* was performed by Singer [3]. In this technique, a bolus of liquid is tagged upstream and detected downstream. The measurement of flow velocity consists of noting the time interval between pulsing the transmitter and receiving the signal, then dividing the distance between the transmitter and the receiver by the time interval. Such a technique is limited to measuring the average flow velocity in a known direction, and has been limited in practice to the measurement of flow in inanimate objects or to the measurement of flow in the extremities.

In 1983, Moran [4] described a new method for the reconstruction of NMR flow images. In this technique, an NMR scan is specifically modulated to be spectroscopically motion sensitized. At the end of data collection, a special reconstruction algorithm yields an NMR image whose pixel values are the joint spatial-flow

density of spins within each pixel. The advantage of flow imaging over other techniques, which are not able to provide spatially resolved information, is that it does not require any special calibrations and could provide flow measurements within each pixel.

The generalized Bloch's equation in the presence of flow will be presented in Section 2. Examples of incoherent flow field characterization will be given in Section 3. The conclusion is in Section 4.

2. Bloch's Equation with Flow

Bloch's equation [5] describes the evolution of magnetization density in the presence of magnetic fields. It also takes into account various relaxation processes empirically. If there exists a flow field within the object in addition to the stationary parts, the Bloch's equation can be modified to take the effects of flow into account. In a Lagrangian reference frame which is rotating at the center Larmor frequency $\omega_0 = \gamma B_0$ and is also translating with a moving group of nuclei, the modified Bloch's equation for the transverse magnetization is,

$$\frac{dM}{dT} = i \gamma G(t) \cdot \left[r_0 + \int_0^t v(r_0; t') dt' \right] M - \frac{M}{T_2} \quad (1)$$

where r_0 is the initial position of a moving group of nuclei at time $t=0$. In equation (1), $v(r_0; t)$ and $M = M(r_0; t)$ are the time dependent velocity vector and the complex transverse magnetization of the moving group of nuclei labelled at an initial position r_0 . In the above equation γ and T_2 are the gyromagnetic ratio and spin-spin relaxation constants, respectively. In equation (1), $G(t)$ is the time dependent magnetic field gradient used to encode various parameters of interest. The effect of the motion of the nuclei is absorbed into the square bracket in eq. (1) which represents the time dependent instantaneous position of the moving group of nuclei. The scalar product gives the magnetic field strength experienced by the group of nuclei while in motion. The solution of eq. (1) is given by,

$$M(r_0; t) = M(r_0; 0) \exp \left\{ i \gamma \int_0^t G(t') \cdot \left[r_0 + \int_0^{t'} v(r_0; t'') dt'' \right] dt' - \frac{t}{T_2} \right\} \quad (2)$$

Equations (1) and (2) are useful when flow or motion effects of the nuclei are being studied. It should be noted that the flow field under consideration here is laminar. If one is dealing with turbulent flow, the situation is more complicated due to the rapid and random motion of each spin. In a later section, we will show how the effect of turbulence could be taken into account.

We will now outline how the solution of eq. (1) given in eq. (2) could be used to spatially map various flow quantities. In this article, we will follow the work of Moran [4] who introduced a function $\Delta(r, v)$ called the joint spatial-flow spin density distribution. The multi dimensional function Δ gives the probability of a spin

to be within the location $\mathbf{r}$ to $\mathbf{r}+d\mathbf{r}$ with a velocity in the range $\mathbf{v}$ to $\mathbf{v}+d\mathbf{v}$. Moran also proposed methods for obtaining the six dimensional quantity $\Delta(\mathbf{r},\mathbf{v})$ using 6-D imaging. The basic idea is described below.

Since each spin can be in motion, its position may be written as

$$\mathbf{r}(t) = \mathbf{r}_0 + \int_0^t \mathbf{v}(\mathbf{r}_0; t') dt' \quad (3)$$

For constant velocity, equation (3) simplifies into

$$\mathbf{r}(t) = \mathbf{r}_0 + \mathbf{v} t \quad (4)$$

We will now define two vector quantities given by

$$\mathbf{q} = \gamma \int_0^t \mathbf{G}(t') dt' \quad (5. a)$$

$$\mathbf{p} = \gamma \int_0^t t' \mathbf{G}(t') dt' \quad (5. b)$$

The detected signal from a volume excited by an r.f. pulse is given by,

$$S(\mathbf{q}, \mathbf{p}) = \iint \Delta(\mathbf{r}_0, \mathbf{v}) \exp[i(\mathbf{q} \cdot \mathbf{r}_0 + \mathbf{p} \cdot \mathbf{v})] d\mathbf{r}_0 d\mathbf{v} \quad (6)$$

A complete data set $S(\mathbf{q},\mathbf{p})$ covering the whole $\mathbf{q}$ - $\mathbf{p}$ space can be obtained by performing a 6-D scan. After a 6-D inverse Fourier transform $\Delta(\mathbf{r},\mathbf{v})$ can be calculated.

In order to vary $\mathbf{q}$ and $\mathbf{p}$ independently, one has to devise special gradient waveforms as discussed in reference [6] by Xiang and Nalcioglu. For example, if we utilize the two gradient waveforms shown in fig. (1), we can manipulate $\mathbf{q}$ and $\mathbf{p}$ independently for the case of constant flow. If the flow is non-stationary, one can devise even more sophisticated gradients, see ref [6].

3. Incoherent Flow Field Characterization

Flow, in general, can be categorized as steady or time dependent. Both of these types of flow can then be subdivided into coherent and incoherent flow. The main difference between coherent and incoherent flow is that in the latter there exists randomness either space or time or both. Whereas the former is subjected to "normal" statistical uncertainties associated with any physical measurement. Table 1 summarizes various types of flow according to the classification introduced.

In the next sections we will discuss several different examples of incoherent flow field characterization. The specific types of flow to be considered are I.B.b, II.B.a, and II.B.c according to the classification given in Table 1.

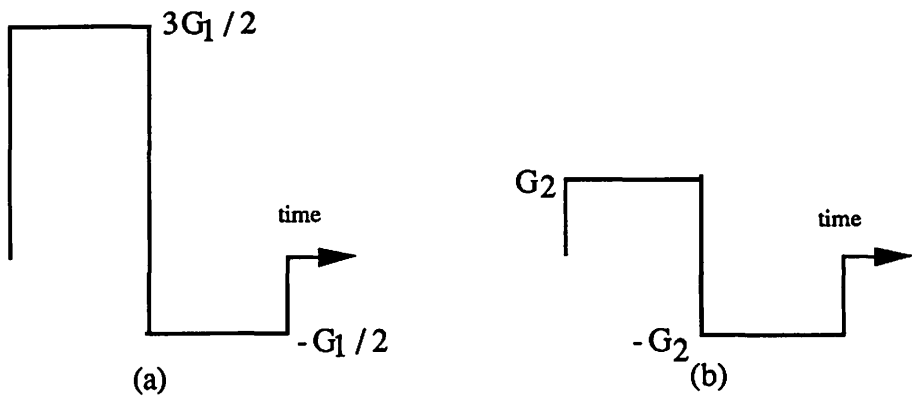


Figure 1 (a) Pure spatial encoding gradient, (b) pure velocity encoding gradient.

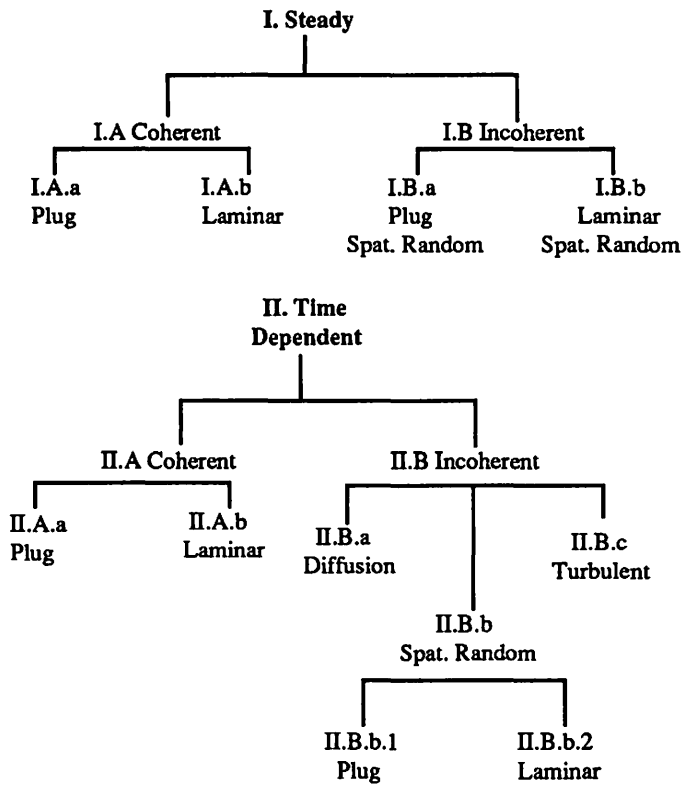


Table 1. Types of flow

3.a Diffusion

Diffusion is an irreversible process which is random both in time and space. It corresponds to zero net flow but a certain amount of transverse magnetization dephasing if magnetic field gradients are present. Thus it results in a reduction of the measured signal amplitude. The effect of self-diffusion can be introduced into the Bloch's equation(1) by adding a term,

$$\nabla \cdot \mathcal{D} \cdot \nabla M \quad (7)$$

where $\mathcal{D}$ is the self-diffusion tensor. In the case of scalar self-diffusion, equation(7) may be simplified into,

$$D \nabla^2 M \quad (8)$$

A method for the measurement of spin diffusion was introduced by Stejskal[7]. His technique was not based on measurements from images, i.e. no spatial maps of D could be obtained. Spatially resolved measurement of diffusion constant was proposed by various researchers[8-11]. A serious drawback of such techniques is that other types of motions corrupt the measurements since they may also cause a certain amount of spin dephasing. It can be shown[12] that the effective diffusion constant, D^* , computed from magnitude images in the presence of coherent bulk flow and incoherent motion is given by,

$$D^* = D - \frac{1}{C_k} \ln | (1-f) + f \prod(p) \exp[2\pi i p \cdot \langle v \rangle] | \quad (9)$$

where f is the fraction of spins which are stationary, $\langle v \rangle$ average bulk flow velocity at a given point, and C_k and $\prod(p)$ are defined by,

$$C_k = \gamma^2 \sum_{j=1}^3 \left\{ \int_0^{TE} \left[\int_0^{t'} G_j^k(t'') dt'' \right]^2 dt' \right\} \quad (10. a)$$

and

$$\prod(p) = \int d^3 u \eta(u) \exp[-2\pi i p \cdot u] \quad (10. b)$$

where η is the distribution function for incoherent flow velocity u . The pulse sequence given in ref.[12] was designed to minimize the contributions from other types of flow by employing motion compensated gradients.

3.b Spatially Random Directional Steady Laminar Flow

There are certain types of media which are comprised of an ensemble of random directional flow channels. Examples of such media include porous materials,

and certain types of biological tissues filled with capillaries or tortuous microvessels. Even though flow in each channel may be steady and laminar, because of the randomness of the flow channels one may still have a finite amount of dephasing of the transverse magnetization. This is due to the motion in flow channels when magnetic field gradients are present. In references[13-14] we have introduced a method for characterizing flow within such media by measuring a quantity called the incoherent diffusivity $D_I(r)$. It is defined by,

$$D_I(r) = \sigma_u^2(r) / 8 \quad (11)$$

where $\sigma_u^2(r)$ is the variance of the random directional flow velocity u as was discussed in Section 3.a within a different context. In equation(11) t is the duration of the gradient waveform applied for the measurement. Several applications of the technique were presented in refs.[15-16]. Some of the assumptions used in refs.[13-16] were critically examined in ref.[17]. There we have considered the effect of the channel length, average channel flow velocity, and the data acquisition time on the signal amplitude. Since the measurement of incoherent diffusivity is based on signal attenuation due to random channel dephasing a clear understanding of the interrelation these variables is crucial for accurate measurements.

3.c Turbulent Flow

Magnetic resonance imaging offers a means for the spatially resolved characterization of turbulent flow. When one deals with turbulent flow the measured signal is attenuated due to the random nature of turbulent flow. In turbulent flow the flow field is random both in space and time. We have previously reported[18-19] that the Bloch's equation can be modified to take into account the turbulent nature of flow. This was achieved by the introduction of eddy diffusivity, D_T , into the Bloch's equation. In this case an additional term given by,

$$D_T \nabla^2 M \quad (12)$$

was included in equation(1). The measurement of D_T is based upon the acquisition of two images the first one being allowed to be affected by turbulent flow whereas a second one in which its affects are minimized. A knowledge of the various imaging parameters which enter into the measurement allows one to calculate D_T on a pixel by pixel basis. Once the eddy diffusivity is measured one can also study the Lagrangian integral time scale, T_L , defined by,

$$D_T = \langle u^2 \rangle T_L \quad (13)$$

4. Conclusion

We have classified various types of flow according to their time dependence and randomness. Three different types of incoherent flow were characterized by a

parameter called the diffusivity. In the case of molecular diffusion it is known as molecular diffusivity. Spatially random laminar flow and turbulent flow were also described in terms of their respective diffusivities. By introducing these terms into the Bloch's equation we were able to show how they may be measured as a function of spatial position by magnetic resonance imaging.

ACKNOWLEDGEMENT

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Computerized Automated Detection of Pneumothorax in Digital Chest Radiographs

Shigeru Sanada, Kunio Doi, Heber MacMahon, et al

Kurt Rossmann Laboratories for Radiologic Image Research,
Department of Radiology, University of Chicago, Chicago, IL

Pneumothoraces are clinically important abnormalities that appear commonly as a subtle, fine line pattern on chest radiographs. Few investigators have reported about detection of pneumothorax using computer. In 1963, Meyers and his colleagues reported that a pneumothorax was rendered clearly visible on a video display by using the "derivative function" image. This paper reports an approach for automated detection of pneumothorax to aid radiologists' diagnosis.

The chest images used here were digitized by a Konica laser scanner. The pixel size is 0.175mm x 0.175mm. The matrix size and gray scale are 2000 x 2430 and 10 bits, respectively. The lung regions were identified by analysis of the horizontal signature and the edge gradient to examine the apical areas selection where subtle pneumothoraces commonly appear. To enhance a subtle pneumothorax pattern, we determined the orientation of the maximum edge gradient, which is obtained by using an edge filter in both vertical and horizontal directions in the digitized images. With this processing, the rib edges are also enhanced. Therefore, to distinguish a pneumothorax from rib edges, we detect the ribs with a technique based on statistical analysis of the edge gradients and their orientations that are included in a small region. Points located on a line which is suspected to be a pneumothorax in apical lung area of this enhanced image, were then detected using a Hough transform.

When a limited angle toward the upper peripheral region is selected for displaying maximum edge gradients in

chest images, apical pneumothoraces and upper margins of posterior ribs were clearly visualized. It was possible to detect pneumothoraces by an appropriate choice of angles and radiuses in the parameter space of the Hough transform. The detected line corresponding to a pneumothorax was displayed on the digitized chest image.

According to our analysis of pneumothorax patterns in chest images, the edges of pneumothorax have slightly larger gradient than that of background trend. However, the gradient of the edges of pneumothorax is toward upper peripheral side, whereas that of the background trend is toward the midlung side. Therefore, an appropriate selection of the orientation of edge gradient makes it possible to detect pneumothorax, even when it is subtle. Since the edge of typical pneumothorax lies continuously on a slightly curved line, a Hough transform is useful for its detection.

We believe that this technique has the potential to be a valuable aid to radiologists for the detection of pneumothorax.

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Projective MR Arteriography and Venography With Interactive 3-D Display

E.M. Bellon, D.H. Feiglin, P.J. Diaz, et al

MetroHealth Medical Center,
Case Western Reserve University, Cleveland, OH

W. Sattin

Picker International, Cleveland, OH

MR Angiography (MRA) has shown considerable potential in non-invasive evaluation of the vascular system. To date this has been primarily confined to evaluation of the carotid bifurcation. The aim of this paper is to show the general applicability of MRA to vascular structures throughout the body.

TECHNIQUE

We utilized 3-dimensional volume acquisition of a tissue slab. The slab orientation, number and thickness of slices, and thus slab volume were user selectable. The sequence incorporated choice of presaturation band selection whether in or out of the plane of section as well as orthogonal to that plane. We thus had the choice of:

- a) no presaturation;
- b) one saturation band, or;
- c) a sandwich of two saturation bands.

The use of two saturation sequences permitted us to acquire data and utilize the minimum basis set angiographic technique (MBS-MRA) as discussed by Sattin⁽¹⁾. This has the ability to display either arterial or venous systems or a combination of both.

The pulse sequence employed a modified field-echo (FE) with user selectable TR in the range 45 to 85 msec, TE non-selectable = 10 msec, and selectable flip angle, usually 25°. Slice

thickness varied from 0.6mm to 2.0mm yielding a slab 3.2 cm to 12.8cm. thick. Acquisition times ranged from 6.6 to 13.2 minutes. Minimum field of view was 25 cm.

All data was acquired on a Picker Vista* 1.5 T imaging system using a linear body coil or a quadrature head coil (for carotid or small body parts).

COMPUTATION

Images were reconstructed during data acquisition so that 2-D cross-sections were available for review, commencing immediately after scan completion. In this format the images are inaccessible to diagnostic interpretation and require minimal additional processing to permit projective display of the selected vascular component, in any plane. Algorithm manipulation of the data allowed visualization of either the arterial or venous systems.

The above manipulation was performed on either the scanner hardware or by tape transfer on the Voxelflinger** workstation. Appropriate rendering of data was available on each system, with interactive display available on the Voxelflinger.

METHODS

Images were acquired from normal volunteers and patients with known vascular disease who had been studied by conventional angiography or Doppler ultrasonography. Regions studied included carotid bifurcation, aortic arch and adjacent great vessels, abdominal aorta and

* Picker International, Highland Hts, OH 44143

** Reality Imaging, Solon, Ohio 44139

renal arteries, aortic bifurcation and iliac system, femoral artery, wrist, ankle and knee. To date we have examined 24 subjects.

RESULTS AND CONCLUSIONS

The study is ongoing and results at this stage are preliminary. The main conclusions to date are:

- a) satisfactory images of arterial and venous systems can be obtained by this method.
- b) careful attention to scan technique, especially with regard to siting of the presaturation band(s) is necessary.
- c) it is possible to visualize small third-order branches subsequent to the image processing techniques described above.
- d) interactive display enhances visualization of small vascular structures, and allows clear viewing of deeper structures without obscuration by overlying tissue.
- e) the minimum basis set method allows complete recognition of arterial and venous morphology.

ACKNOWLEDGEMENT:

We would like to thank Ed Kubiez, R.T. and Michael Pettit, R.T. for their contribution to this study.

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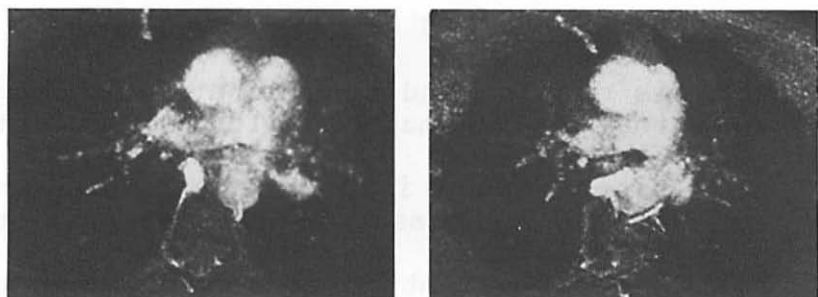


FIGURE 1: THORAX

- a) 45° oblique coronal section demonstrates pulmonary artery bifurcation, azygos system, and internal mammary arteries. b) 20° RAO axial section demonstrates azygos system and vertebral venous plexus. Superior vena cava is not seen due to superior placement of presaturation band. Azygos system is visible because of flow direction and is thus unaffected by presaturation band.

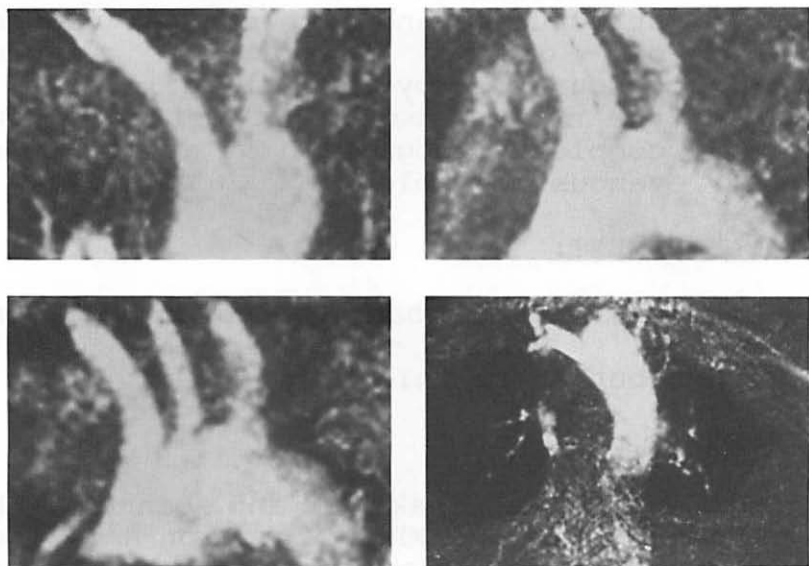


FIGURE 2: AORTIC ARCH

- a,b,c) Arterial phase with progressive rotation to 45° oblique. The arch is displayed in transverse projective view in (d) which shows take-off of innominate artery and its bifurcation.

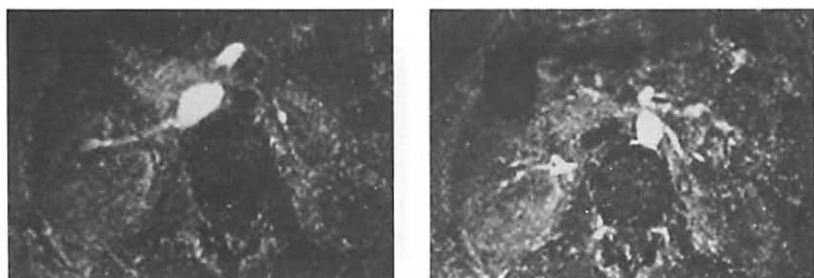


FIGURE 3: RENAL VENOUS AND ARTERIAL SYSTEMS

a,b) Axial sections with presaturation bands above (vein) and below (artery) plane of section. Note absent signal from aorta and renal arteries in (a) and similarly absent signal from inferior vena cava in (b).

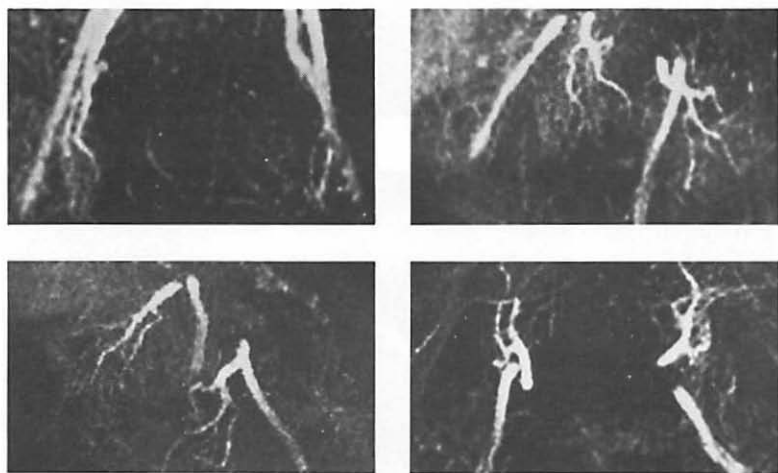


FIGURE 4: ILIAC ARTERY

Arterial phase coronal (a) and rotated coronal (b,c) images of iliac artery system in patient with large uterine leiomyoma. Image (d) is transverse projective display showing iliac and gluteal arteries.

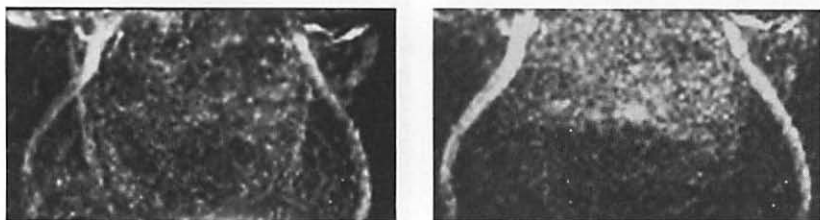


FIGURE 5: FEMORAL ARTERY

a,b) Femoral arteries with inferior presaturation band. Note distracting background noise in non-subtracted image (a). Minimum basis subtraction set technique (b) allows enhancement of femoral arteries in relation to surround. Note artifact in upper field in (b) due to current algorithm.

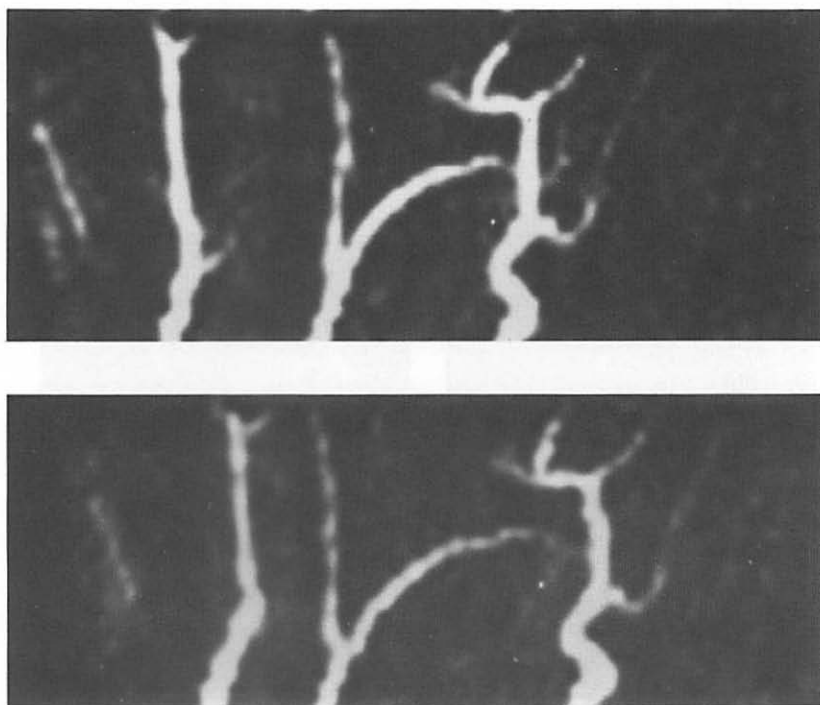


FIGURE 6: WRIST

a,b) Arterial phase coronal projections of wrist showing radial and ulnar arteries and transverse palmar arch. Note ability to visualize small caliber vessels using subtraction technique.

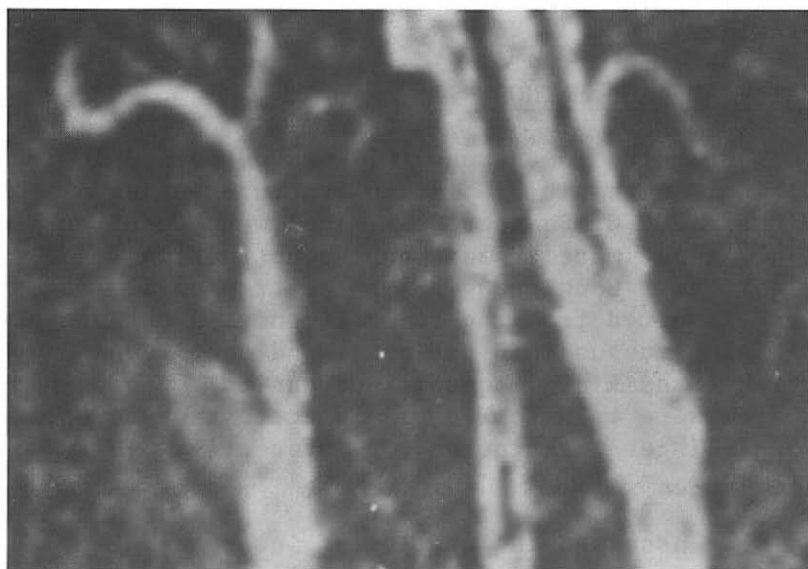
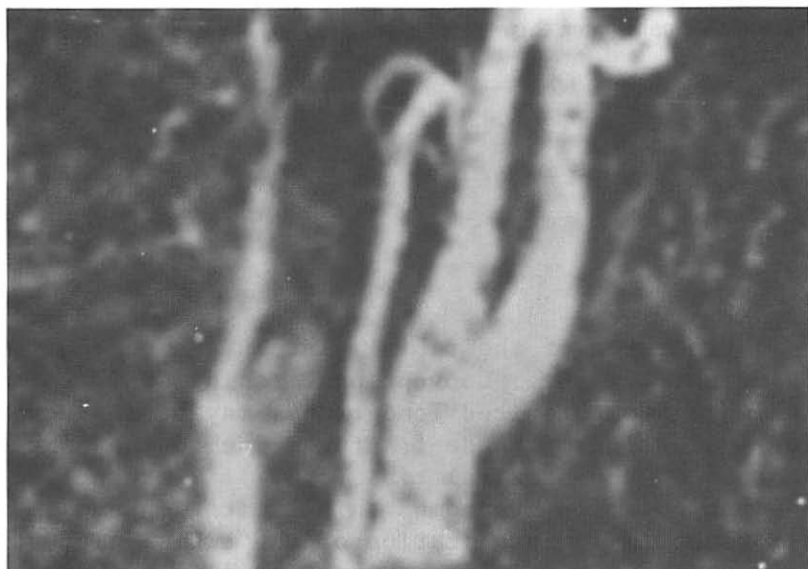


FIGURE 7: CAROTIDS

a,b) RAO & LAO rotated coronal sections show complete occlusion of right internal carotid artery with visualization of only a short proximal stub.

Interactive 3-D Display for Assessment of Tibial Plateau Fractures

W.D. Murphy, P.J. Diaz, J.R. Crass, et al

MetroHealth Medical Center, Case Western Reserve University,
Cleveland, OH

Fractures of the tibial plateau are common injuries(1,2,3,4). Conventional radiography, including Computerized Tomography, may be inadequate for evaluation of these fractures due to the complex anatomy of the proximal tibia(5,6,7). Interactive 3-D manipulation overcomes this limitation and allows optimal visualization of the tibial plateaus. We report our initial experience in diagnosis and assessment of tibial plateau fractures using the VoxelFlinger* workstation for interactive 3-D viewing.

MATERIALS AND METHODS

Computed Tomography (CT) was performed in 10 patients with tibial plateau fractures using a Picker 1200 CT Scanner**. Images were acquired with a 512 x 512 matrix and bone reconstruction algorithm. Contiguous 2mm thick transaxial images were acquired from the femoral condyles through the tibial plateaus in 9 patients, and contiguous 3mm thick transaxial images in one patient. The 2-D images were transferred via magnetic tape to the VoxelFlinger workstation for interactive 3-D viewing.

We assessed the utility of interactive manipulation according to the following criteria:

* Reality Imaging, Solon, Ohio 44139

** Picker International, Highland Hts., Ohio 44143

- 1) Confirmation of fracture
- 2) Ease of visualization of fracture lines
- 3) Degree of impaction and displacement
- 4) Extent of expansion (explosion) of the plateau.

RESULTS

The data could be transferred to the workstation, reviewed and imaged within 30-45 minutes. Once reviewed, it became apparent that the 3-D images better characterized the fractures as compared to the transaxial CT images and orthogonal multiplanar reconstruction (MPR). The 3-D images were found to be an advantage in visualizing sloping and irregular plateau depressions and impactions (Figure 1). Oblique fractures could be rotated for optimal visualization and subtle abnormalities such as minimal plateau depressions were easily seen (Figure 2).

The fractures were classified from the CT images according to Hohl(8) (Table I). The data from the 3-D images resulted in a change of classification in one case, from split depression to comminuted upper tibia (bi-plateau).

Table II summarizes the degree of plateau depression and fragment separation as measured from the CT and VoxelFlinger images. Although the actual measurements differed by only a small amount (3mm or less), the 3-D images were more accurate in depicting the maximum amount of plateau depression.

DISCUSSION

Fractures of the tibial plateau are difficult to assess radiographically due to the complex anatomy of the proximal tibia(5,6,7). Open reduction is usually performed if the plateau is depressed 5mm or greater(8). Other factors which require assessment for determining treatment include the degree of fragment separation and comminution.

Accurate evaluation is essential in order to maintain adequate range of motion and to prevent joint instability and early degenerative change(6).

CT has largely replaced conventional tomography in the evaluation of tibial plateau fractures(5,6). However, the transaxial sections obtained by CT may not be accurate for assessment because of the slope of the plateau(9). In addition, because the fractures are often oblique, neither transaxial sections nor coronal and sagittal reconstructions are capable of displaying them adequately.

Interactive 3-D viewing lends itself well to the evaluation of tibial plateau fractures. The image can be manipulated so that the fracture can be seen in its most optimal projection. The 3-D format allows for excellent characterization of plateau depression and expansion.

Several techniques were valuable in fracture assessment. In the interactive MPR mode, 3 orthogonal planes could be viewed and manipulated simultaneously. This allowed the relationships between complex fractures, depressions and fracture fragments to be assessed immediately (Figure 3). By using the "Cut Plane" and "System Parameter" (TRIM) modes, overlying and surrounding structures such as casts and femoral condyles could be removed, allowing better visualization of the plateau: for example, removal of the condyles by this method permitted unobstructed en face viewing of the plateau surface from above.

The 3-D images could be manipulated interactively for optimal viewing as opposed to 2-D CT reconstructions, where the planes were preset. The degree of plateau depression and fragment separation could be measured directly, allowing for more accurate measurements. As a Level I Trauma Center, the majority of cases at our hospital resulted from severe injuries and open reduction was necessary. With less severe injuries, accurate

measurements are essential in helping to determine the method of treatment.

In summary, the VoxelFlinger allows easy interactive manipulation of images for optimal display of fractures and morphology. Overlying and surrounding structures, e.g., casts, bandages and femoral condyles can be removed from the image where they would otherwise interfere. Fractures can be seen in multiple planes and the plateaus can be visualized en face. In many cases, this provided additional information which permitted complete fracture characterization.

ACKNOWLEDGEMENT:

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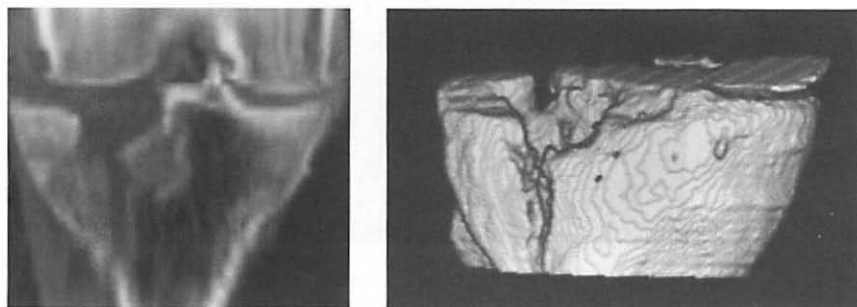


Figure 1 a,b: LATERAL PLATEAU FRACTURE: Coronal CT reconstruction (a) and 3-D image (b), showing relationship of plateau depression to fragment lines. Note removal of condyles except for small fragment medially.

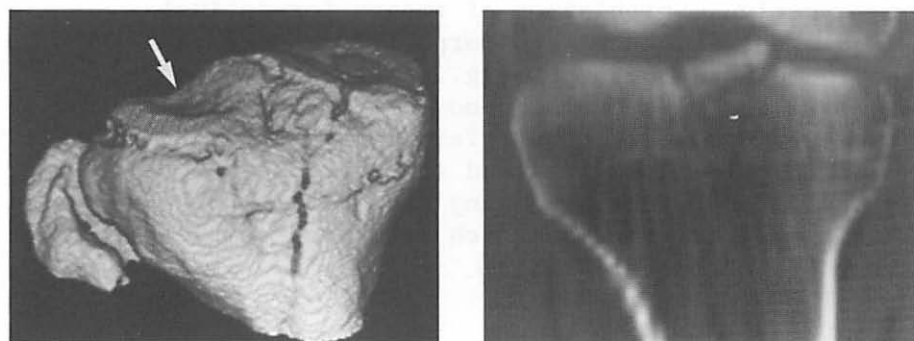


Figure 2a,b: 3-D image showing minimal depression of posterior aspect of lateral plateau (arrow) not appreciated on original CT sections or reconstruction (b). Note extension fractures involving tibial spines.

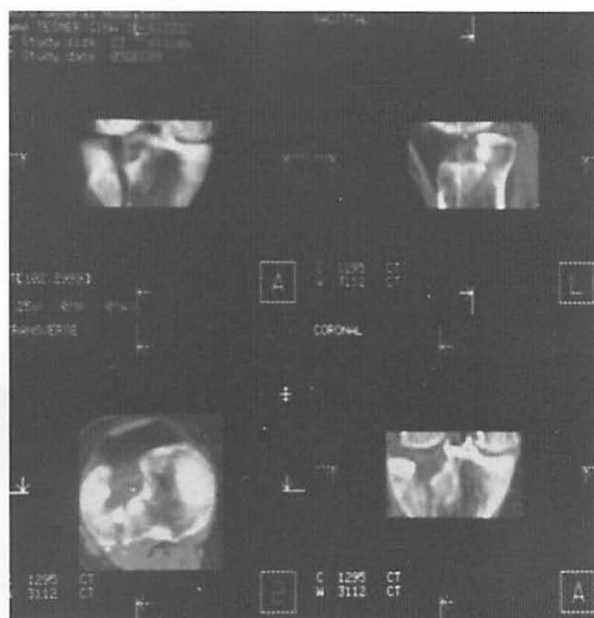


Figure 3: Multiplanar Reconstruction screen showing simultaneous images and relationship between plateau depression, fracture and fracture fragment. Note that as selected plane of section is varied on any of these orthogonal projections, it automatically changes to show the corresponding planes in each of the other projections - and does so interactively. (Same Case as Figure 1).

Table I: Classification of Tibial Plateau Fractures

<u>TYPE OF FRACTURE</u>	<u>METHOD OF EVALUATION</u>	
	<u>CT</u>	<u>VOXELFLINGER</u>
Central Depression	1	1
Split Depression	5	4
Comminuted Upper Tibia (Bi-Plateau)	4	5

TABLE II: MEASUREMENTS OBTAINED BY CT vs. VOXELFLINGER
(ALL MEASUREMENTS IN MILLIMETERS)

<u>FRACTURE TYPE</u>	<u>METHOD OF EVALUATION</u>			
	<u>C T</u>		<u>VOXELFLINGER</u>	
	<u>PLATEAU DEPRESSION</u>	<u>FRAGMENT SEPARATION</u>	<u>PLATEAU DEPRESSION</u>	<u>FRAGMENT SEPARATION</u>
Central Depression ⁺	<2	<2	3	<2
Split Depression	5	2	5	2
Split Depression	12	4	12.5	5.5
Split Depression	10	7	10.5	6.0
Split Depression	12	5	12	5
Comminuted ⁺⁺ Upper Tibia	16	5	19	5
Comminuted Upper Tibia	5	4	5.5	3.5
Comminuted Upper Tibia	14	7	14.5	6.5
Comminuted Upper Tibia	15	1	15	1
Comminuted Upper Tibia	12	1	12	1

⁺ Voxelflinger showed subtle depression not appreciated on CT

⁺⁺ Classification changed from Split Depression based on Voxelflinger data

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“Global Contrast” Based Image Processing

Fred Greensite and Richard Buxton

Department of Radiological Sciences, University of California-
Irvine Medical Center, Orange, CA

1. Introduction. Contrast in an imaging acquisition is defined in terms of the magnitude of the signal value difference between two neighboring regions. Thus, the two quantities of paramount importance in image processing, contrast and resolution, seem to be intrinsically local in nature. Reflecting this are the many local image enhancement techniques involving convolutions, typically effected by repeated local application of templates which are translated throughout the image. But there is also a collection of global methods defined independently of the immediate spacial relationships between voxels, a prototypical example being histogram equalization. More generally, segmentation (which is the forced classification of pixels according to decision algorithms applied to their totality of characteristics) may employ both local and global information. Our intention here is to examine the implied “global” aspects of contrast. This will ultimately suggest generalizations of the current notions of the contrast inherent in an imaging acquisition, with various implications for the analysis of image quality, and for the creation of new classes of images from these acquisitions. Specifically, a new image processing algorithm is identified, which creates contrast from textural distinctions between tissues using global determinants of texture. Critical features of this approach are the recognition of “metric” and “non-metric” determinants of acquisition contrast, and the avoidance of *ad hoc* application of templates or probabilistically based decision processes.

It should be mentioned at the outset that a medical imaging technology capable of optimally taking advantage of this methodology does not necessarily presently exist (though ultrasound and MRI seem likely candidates for its application). At the moment, we believe our investigation to be of interest primarily for its mathematical conclusions regarding the quantification and presentation of the useful imaging content in an acquisition.

2. Global Contrast. The principal aim of medical image production is to create distinctions between tissues. Once an object is distinguishable, it is of less importance whether it is “well” distinguished or “superbly” distinguished. From a global standpoint, the more distinct tissues identified the better - and an image which adequately distinguishes ten tissues is generally

better than one which distinguishes two of them ten times as well as any pair of tissues in the first image, while failing to delineate the other eight tissues. Therefore, we desire to generalize the definition of contrast to be more reflective of the number of "adequately" distinguished tissues. For example, one rejected candidate for Global Contrast would be the standard deviation of the image signal values divided by the standard deviation of the noise (e.g. as used in [1]) - since this strongly favors large well distinguished tissues and de-emphasizes the importance of small adequately distinguished tissues.

We begin with the supposition that similar tissues map to the "same" location in signal space (signal space being the continuum representing the possible signal values which may be measured; it may be multi-dimensional e.g., in MRI it could be the set of ordered triplets representing T1-, T2-, and proton density-weighted signal values). If there is no noise, and two tissues are the same if and only if they have the same signal value, then

$$\text{number of distinct tissues} = \frac{1}{N} \sum_{w_i} \frac{1}{h(M(w_i))} = \sum_{s_j} 1, \quad (1)$$

where the first sum is over all the voxels w_i which partition the field of view V , $M(w_i)$ is the point in signal space S assigned to voxel w_i , h is the histogram of the acquisition normalized to the N voxels in the field of view (i.e. h is the probability density function of the acquisition), and the second sum is over all points s_j in signal space such that there is a voxel w_i for which $s_j = M(w_i)$. In the setting of noise (1) can be generalized using the change of variable formula (see [2])

$$\int_A f \circ g \, d\lambda_A = \int_B f \cdot \left[\frac{d\mu}{d\lambda_B} \right] d\lambda_B, \quad (2)$$

(e.g. A is V , B is S , $f = 1/h$, $g = M$, $d\mu/d\lambda = h$) so that "Global Contrast" (GC) can be defined as

$$GC \equiv \frac{1}{2\epsilon(\nu)} \int_{S_{\epsilon(\nu)}} ds \approx \frac{1}{N} \sum_{w_i} \frac{1}{h(M(w_i))}. \quad (3)$$

In (3) it is understood that h is the normalized histogram convolved with a Gaussian density whose standard deviation is some multiple $\epsilon(\nu)$ of the noise standard deviation ν (where it is assumed, as in MRI, that ν is uniform throughout the image), so that $S_{\epsilon(\nu)}$ is the volume in signal space having a non-negligible probability density of being mapped to by some voxel in the field of view (non-negligible as gauged by $\epsilon(\nu)$). In particular, the "number of distinct tissues" in (1) generalizes to the noise normalized volume in signal space accessed (the middle expression in (3), which generalizes the sum on the right side of (1)). Without the decision making algorithms of segmentation, one cannot do better. However, it is our contention that such decision

processes belong to specific engineering applications and not to basic analysis of contrast or information, since segmentation decisions are always in danger of being wrong.

It should be noted that, unlike the signal-to-noise ratio, there is no simple inverse relationship between GC and resolution. For this reason one could propose that resolution be chosen such that GC is optimized. [For example, consider two tissues arranged in a checkerboard fashion. With constant dose or imaging time, at either very low or very high resolution GC will tend to 1 (meaning that only one tissue is identified). Resolution should be chosen so that GC is close to 2.] Also, note that as the noise standard deviation tends to zero, GC reduces to (1), while as the noise standard deviation becomes large, GC becomes 1. In this sense GC is a true generalization of the number of distinct tissues identified.

At this point it is of interest to compare (3) with the measurement of information content given by information theory [3], namely (ignoring noise)

$$HE = \frac{1}{N} \sum_{w_i} \log_2 \left[\frac{1}{h(M(w_i))} \right] = - \sum_{s_j} h(s_j) \log_2 h(s_j). \quad (4)$$

HE refers to "histogram entropy", and it is the classical information content embodied in the assignment of a collection of voxels $\{w_i\}$ to the signal values $\{M(w_i)\}$. The appeal of GC is that it is independent of relative tissue volume, whereas HE is very dependent on the relative volumes of tissues. Since we are concerned with rewarding that image which identifies the most tissues (regardless of their volume), GC would seem to have some advantage in its economy of dependencies (nevertheless, the similarity of (3) and (4) is striking). GC is suitable for addressing questions concerning optimal selection of parameters controlling an acquisition (e.g. in reference to MRI, relevant questions addressed would be: "when should imaging matrix size be traded for increased number of excitations?," or, "which TE is best for a T2-weighted sequence?," etc.).

3. Generalized Images. Medical images are typically a graphical depiction of the properties of a set of voxels. Usually these properties are physical parameters of the tissue. However, they could also be abstract properties of the voxels. In particular, each voxel w has the information content $-\log_2 h(M(w))$. If we image this information content by assigning each w_i the new value $-\log_2 h(M(w_i))$ we obtain an image in which contrast is independent of the distance between the signal values given the voxels by the acquisition - a non-metric image, based on non-metric contrast (as opposed to the standard images, this new image is independent of the signal space metric). We can accomplish the same thing if we eliminate the logarithm and image h directly (the log does not impact the information content of the image). We can actually do somewhat more. Since $\epsilon(\nu)$ (which defines h) is unspecified, we can produce a continuum of images, each with a different

value of $\epsilon(\nu)$. These images are referred to as MT-images ("MT", stands for "measure-theoretic", and is used for reasons considered elsewhere [2,4]). Thus *different MT-images are produced by filtering in signal space rather than filtering in the field of view space.*

We now further explore some properties of these new images:

DEFINITION 1: A *tissue* is some specified collection of voxels.

Consider the random variable which is the measured signal value difference between two randomly chosen voxels, one from each of two different tissues. The contrast-to-noise ratio is the expectation of this random variable divided by its standard deviation - in other words

DEFINITION 2: The *contrast-to-noise ratio* (CNR) of two tissues is given by

$$CNR = \frac{s_1 - s_2}{\sqrt{\text{var}_1 + \text{var}_2}}, \quad (5)$$

where var_1 , var_2 , denote the variance of the signal values of the two tissues, and s_1 , s_2 are the mean signal values of the two tissues.

DEFINITION 3: A *standard image* from an acquisition is one in which CNR between two tissues is dependent on the difference in the distances from a fixed point in signal space that the signal values associated with two tissues have.

For example, the image created by the original measured signal values is a standard image (the fixed point being the origin). It is interesting that in a certain limit, MT-imaging also produces a standard image, and in this sense MT-imaging is a more general means of producing images from an acquisition.

THEOREM 1: Standard imaging is a special case of MT-imaging. In particular, in the limit as $\epsilon(\nu) \rightarrow \infty$, CNR in the MT-image is

$$CNR = K \cdot \frac{\|s_1\| - \|s_2\|}{\sqrt{2\nu}}, \quad (6)$$

where $\|s_1\|$ and $\|s_2\|$ represent the distances from s_1 and s_2 to the mean signal value of the acquisition, and K is the ratio of the arithmetic mean to the root means square of these two values (K is always between 0.7 and 1).

Theorem 1 is proven by application of Definition 2 to the definition of h (as the convolution of the normalized histogram with a Gaussian density of standard deviation $\epsilon(\nu)$), and applying L'Hospital's rule. An example is given in Figure 1.

THEOREM 2: Two tissues having zero CNR in a standard image will in general have non-zero CNR in MT-images if they differ in the variance of their signal values.

An example of this is seen in Figure 2. While it is possible to visually identify the embedded tissues in the standard image using a tiny window, this precludes viewing the general tissue environment (e.g. seeing the other tissue). Further, a large *CNR* increase is effected in the MT-image. Note also that histogram equalization is not particularly efficacious in this example.

4. Texture and Contrast. MT-imaging is a mechanism for converting texture into contrast. As in Figure 2, it may certainly occur that distinct tissues will not be recognized as such if their mean signal values are very close (or even identical) and their textural variations are small compared to the dynamic range of the image. The MT-image then converts their higher statistical properties into true contrast - and this is accomplished without mechanisms which may contaminate the data (and which may be unreliable), such as those characterizing segmentation. [We do not mean to slight segmentation - we only argue that segmentation decisions are not inherent in the data, while MT-imaging is.] Neither is recourse made to texture templates which contain various *ad hoc* properties (e.g. their spacial extent, and their particular matrix values).

We now will examine some subtleties of the relationship of non-metric contrast and texture.

DEFINITION 4: A *texture* is the collection of statistical properties of the measured signal values of a tissue.

DEFINITION 5: For each of two tissues, subtract the mean signal value of that tissue from each voxel in that tissue. *First order NMC* is the *CNR* in the MT-image formed from the new signal values of these two tissues. Second order NMC is the *CNR* of the two tissues in the MT-image of this MT-image, and so on recursively for the *n*th order NMC.

We will refer to first order NMC in the following as just NMC. Also, we will assume below that there are sufficiently many voxels in a tissue to adequately reflect the noise properties of the acquisition, and that the MT-images referred to below are those obtained directly from the histogram without any convolution with a Gaussian.

DEFINITION 6: A tissue having a *linear* texture is a collection of voxels whose signal values are distributed on a finite interval in signal space such that the number of voxels having a particular signal value in this interval varies linearly with its absolute distance from the mean signal value of the tissue. If the slope of this distribution is zero (so that the signal values are uniformly distributed on the interval), then the texture is termed *white*. If the slope is negative then the texture is termed *linear off-white*. A tissue having a *Gaussian* texture is a collection of voxels whose signal values are normally distributed (this texture is also off-white).

Since the metric doesn't contribute to NMC, we should be interested in what it actually does depend on. It would seem to be obvious that, since MT-

signal value is determined by the histogram of the signal values, NMC must be heavily dependent on the difference in volume between the two tissues. Therefore, the following theorem is non-intuitive and surprising:

THEOREM 3: Let the number of voxels in each of two tissues be m_1 and m_2 . Let $\sigma_1 \leq \sigma_2$ be the widths of the domains in signal space for which the histograms of each tissue are non-zero for linear textures, or represent their respective standard deviations for Gaussian textures. Then

- 1) For two tissues with white texture,

$$NMC = \sqrt{\frac{\sigma_2}{\sigma_1} - 1}.$$

In particular, NMC is independent of the relative volumes of the two tissues, and increases without bound as $\sigma_2/\sigma_1 \rightarrow \infty$.

- 2) For two tissues with linear off-white textures,

- a. if $\sigma_2/\sigma_1 \gg m_2/m_1$, then as (σ_2/σ_1) becomes large NMC tends to $2\sqrt{2}$,
- b. if $\sigma_2/\sigma_1 \ll m_2/m_1$, then as σ_2/σ_1 becomes large NMC tends to $\sqrt{2}$,
- c. for σ_2/σ_1 close to 1, $NMC \sim (\sigma_2/\sigma_1 - 1)$.

- 3) For two tissues with Gaussian texture

- a. if $\sigma_2/\sigma_1 \gg m_2/m_1$, then as σ_2/σ_1 becomes large NMC tends to $(2/\sqrt{3} - 1)^{-1/2} \approx 2.54$,
- b. if $\sigma_2/\sigma_1 \ll m_2/m_1$, then as σ_2/σ_1 becomes large NMC tends to $(\sqrt{2} - 1) \cdot (2/\sqrt{3} - 1)^{-1/2} \approx 1.05$,
- c. for σ_2/σ_1 close to 1, $NMC \sim k(\sigma_2/\sigma_1 - 1)$, where $k = [1/(2\sqrt{2})] \cdot (2/\sqrt{3} - 1)^{-1/2} \approx 0.90$.

This theorem is proven by direct substitution of the texture definitions into the equations for CNR and NMC as given in definitions 2, 5, and 6.

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FIGURE 1. **A** is a proton density weighted MR image of a normal brain. **B** is the MT-image with $\epsilon(\nu) = \nu$. **C** is the MT-image with $\epsilon(\nu) = 30\nu$. Though windowed a little differently, **A** and **C** are nearly indistinguishable in terms of Grey matter/White matter CNR (2.80 versus 2.73 in **A** and **C**, respectively).

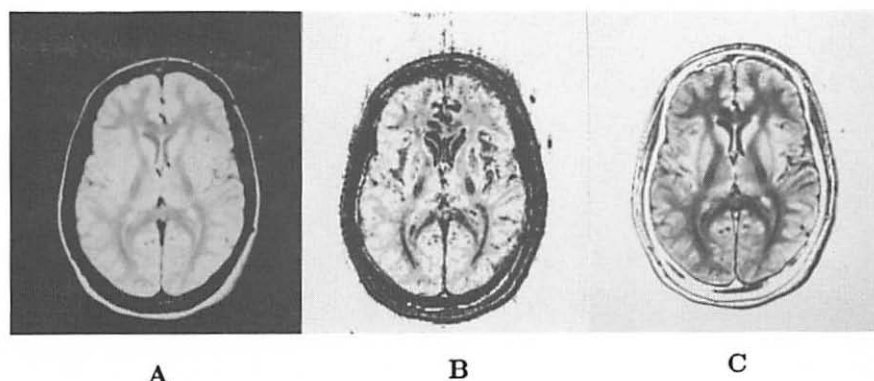
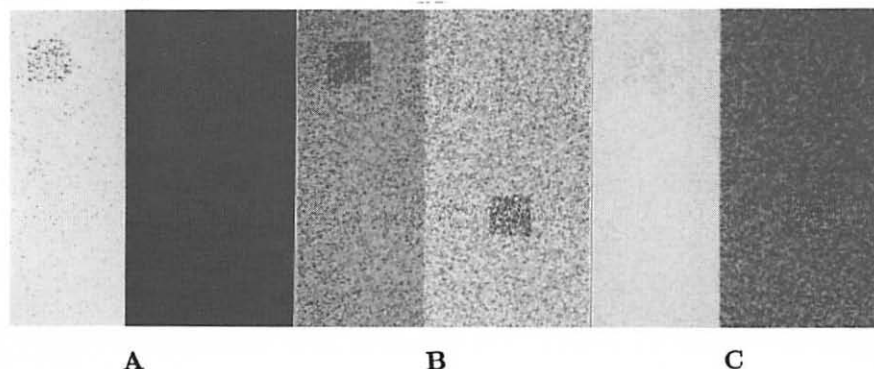


FIGURE 2. **A** is a numerical phantom. The left side of the image has mean signal value 200, while the right side has mean signal value 100. Gaussian noise of standard deviation 1 has been added throughout, except that there is a small region in the upper left and lower right having standard deviation 2, these representing tissues distinct from their background. In a standard image (e.g. **A**) the only way an embedded tissue can be seen is with a window width near 1, precluding visualization of the general tissue environment (e.g. the tissue in the lower right). CNR for the embedded tissues and their background is nominally zero (measured with ROIs to be 0.03 for the left sided tissue pair). **B** is the MT-image made from the signal values in **A** with $\epsilon(\nu) = \nu$. CNR for the left sided tissue pair is 0.59. **C** is the histogram equalization of the original signal values of the phantom. CNR for the left sided tissue pair is measured to be 0.14.



Tomographic Reconstruction

Three-Dimensional Reconstruction of Magnetic Resonance Images: Comparison of Surface and Volume Rendering Techniques

Philipp Lang, Peter Steiger, Thomas Lindquist, et al

Department of Radiology, University of California, San Francisco,
San Francisco, CA

ABSTRACT

MR imaging studies of 33 patients with various disorders of the musculoskeletal system were reconstructed using surface and volume rendering techniques. Surface reconstruction provided a more accurate display of the pathoanatomy than volume reconstruction when multiple objects with anatomic overlap had to be demonstrated. Volume reconstruction was characterized by greater detail than surface reconstruction in demonstrating fine anatomic structures. Both methods were limited by the need for disarticulation lines surrounding the object in the 2-D images to exclude other structures with signal intensity similar to the object from the 3-D display.

INTRODUCTION

Magnetic resonance (MR) imaging has been established as an important diagnostic modality for evaluating the musculoskeletal system that supplements and often replaces computed tomography (CT). Despite its multiplanar imaging capability, MR imaging is currently limited by a two-dimensional display of frequently rather complex three-dimensional structures. Conception of the spatial configuration of an object therefore requires mental integration of a series of two-dimensional MR images. Although radiologists are accustomed to this type of image analysis, it may pose a difficult problem for the clinician who is treating the patient.

In CT, three-dimensional (3-D) reconstruction of a series of two-dimensional scans has already been widely used for preoperative planning (1-4). 3-D reconstruction of MR images has been limited due to technical problems. Only recently, improvements in MR acquisition and 3-D software techniques have facilitated 3-D reconstruction of MR images (5-10). The 3-D image quality that can be achieved with the different 3-D rendering

techniques available for generating 3-D MR image displays has, however, not been compared yet.

In this study, we produced 3-D MR reconstructions in 33 patients with various disorders of the musculoskeletal system. Surface and volume reconstructions were obtained in all 33 patients. Image quality, diagnostic results and technical aspects of both techniques were prospectively evaluated.

METHODS

Thirty-three consecutive patients who had been referred to our institution for a musculoskeletal MR examination were selected for 3-D reconstruction of MR images. MR imaging studies of the hip, knee, ankle, shoulder or wrist were obtained in 13, 10, 4, 4, and 2 patients, respectively. MR images were generated on a General Electric Signa system operating at a field strength of 1.5T. Imaging studies included T1-weighted (TR=300-500 msec, TE=12-30 msec) and T2-weighted spinecho (TR=1800-2500 msec, TE=80-240 msec) as well as T2*-weighted gradient-echo (GRASS: gradient recalled acquisition in the steady state, TR=50-100 msec, TE=20-40 msec, $\theta=10-30^\circ$) sequences. Hip studies were produced using a circumferential body coil or a Helmholtz coil; knee and ankle scans were generated with a lower extremity coil; shoulder imaging was performed employing a pair of counter-rotating current-loop-gap resonators, and wrist images were acquired with a special wrist coil. FOV was kept as small as technically feasible in order to obtain a high spatial resolution of the MR images. Image matrix varied from 256x192 to 256x256.

Two-dimensional and 3-D image processing was performed on an independent imaging system manufactured by Dimensional Medicine Inc. (Maxiview; Motorola 68020 processor; 8 MB RAM; 766 MB hard disk; 4 MB graphics memory; 19 in - color display). 3-D displays of the different tissues were computed on the basis of the T1 or the T2-weighted spinecho or the T2*-weighted gradient-echo images (Fig. 1). The sequence that demonstrated the best contrast for a given tissue was usually selected for 3-D reconstruction.

When other structures had a similar signal intensity than the tissue in question, a manually or automatically drawn disarticulation line surrounding the object was used to image only what was desired in the 3-D display (Figs. 1, 2). Disarticulation lines were selected by the operator on a slice-by-slice basis. Because the use of a disarticulation line may result in a step-like outer contour of the object in the 3-D display (7), a disarticulation surface interconnecting pairs of upper and lower disarticulation lines was computed (Fig. 1).

The data were resampled by linear interpolation to generate a uniform resolution in all three dimensions (Fig. 1). The resultant volume consisted of cubic volume elements which formed the basis for all further processing.

Three-dimensional displays were then generated using surface and volume rendering techniques (Fig. 1). In surface reconstruction, only the surfaces of the objects were computed using 3-D boundary detection; a voxel was considered part of the object when 1.) its signal intensity fell within a predefined range of signal intensities representative for the structure in question and 2.) when it was located within a disarticulation surface in case disarticulation lines had been added to the image. In volume reconstruction, all voxels not only those located at the object surface were preserved and displayed in the 3-D image. The grey value of a voxel in the 2-D image was transferred into a corresponding color and transparency in the 3-D volume rendition using an empirically defined tissue classification table. When disarticulation lines had been added to the 2-D images, only those voxels that were located within a disarticulation surface were displayed in the volume reconstruction. In both surface and volume reconstruction, the different objects (in the knee for example anterior and posterior cruciate ligaments, menisci, and osseous structures, i.e. femur, tibia, patella, and fibula) were simultaneously displayed using different colors and opacities.

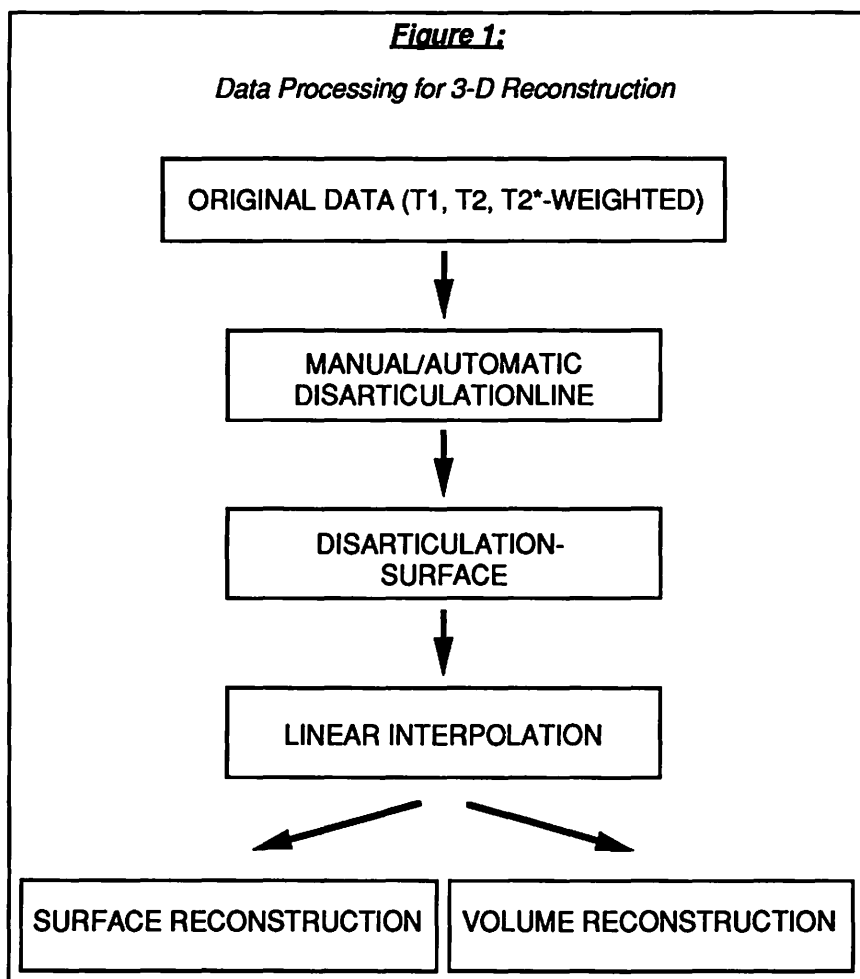
RESULTS AND DISCUSSION

Surface reconstruction

In imaging the hip, knee, ankle, shoulder and wrist, 3-D surface reconstruction provided sufficient anatomic information in most of the cases. Surface reconstruction was particularly good in demonstrating the spatial relationship between different, overlapping objects. In the knee, for example, the orientation, the origin and the point of insertion of the anterior (ACL) and posterior cruciate ligaments (PCL) were clearly delineated in all 10 patients (Fig. 2C).

Surface reconstruction was, however, limited when fine anatomic structures such as the sacroiliac (SI) joint had to be displayed. In imaging the pelvis, the SI joint could not be demonstrated in 40% of the patients. In general, fine anatomic detail was often obscured in surface reconstruction. In addition, artifactual irregularities were frequently observed along the outer contour of the femur, tibia, and humerus.

Surface reconstruction requires 3-D boundary detection and displays only a subset of the data available in the 2-D scan, i.e. the object surface. Exclusion of voxels that are not considered to be



part of the object surface from 3-D display may cause both failure to demonstrate a structure such as the SI joint as well as irregularities in the outer object contour.

Volume reconstruction

Volume reconstruction was characterized by excellent anatomic detail. Volume reconstruction was, however, limited when several structures that demonstrated anatomic overlap were displayed simultaneously. The orientation, the origin and the insertion of the cruciate ligaments were difficult to evaluate in 3-D volume reconstructions of the knee (Fig. 2D). In 7 of the knee patients, the ACL incorrectly appeared to be located posterior to the

PCL (Fig. 2D). This was in part caused by the high transparency effect of the volume reconstruction.

Fine anatomic structures such as the SI joint were, however, clearly delineated in 3-D volume reconstruction. 3-D image artifacts along the contour of the femur, tibia, and humerus were less frequently seen in volume reconstruction than in surface reconstruction.

Volume reconstruction preserves all information contained in the 2-D MR images. Exclusion of voxels from 3-D display is not required in using volume rendering techniques. Computing time is, however, increased by a factor of 8 - 10 in volume reconstruction when compared to surface reconstruction, because significantly more voxels need to be rendered.

Disarticulation

Both surface and volume reconstruction required manually or automatically defined disarticulation lines surrounding the object in the 2-D MR images (Fig. 2B). Although MR imaging affords good soft-tissue contrast, many different structures frequently display similar signal intensity in the 2-D image. Any signal intensity based surface rendition or any tissue classification that transfers 2-D signal intensity values into different colors and transparencies in volume rendering would therefore include structures other than the object to be displayed; the resultant 3-D images would give a misrepresentation of the true anatomy. Therefore, disarticulation lines are needed that help to image only what is part of the object in the 3-D display (5,7). The introduction of disarticulation lines in the 2-D images is, however, time-consuming since it is performed on a slice-by-slice basis; at present, it represents a major limitation for both 3-D surface and volume rendering of MR images.

CONCLUSION

In most patients, both surface and volume reconstructions provide a diagnostically useful 3-D display of the pathoanatomy that can be useful to the surgeon for preoperative planning. Surface reconstruction is superior to volume reconstruction when the spatial relationships between various objects with anatomic overlap need to be displayed. Volume reconstruction is better than surface reconstruction in demonstrating fine anatomic detail. Both methods are currently limited by the need for disarticulation lines that surround the object to be imaged. In the future, software routines that provide automatic definition of these disarticulation lines without operator interaction will greatly enhance the use of 3-D rendering techniques for MR imaging.

Figure 2:**3-D MR Surface and Volume Reconstruction of the Knee in a 33-year-old Patient**

Fig. 2A:
2-D MR image (spinecho, TR=500 msec, TE=20 msec). Femur, tibia, patella, and fibula demonstrate high signal intensity. Hoffa's fat pad (1) and soft-tissue posterior to the distal femur (2) display similar signal intensity than the osseous structures.



Fig. 2B:
Selection of voxels with signal intensities representative for bone for 3-D reconstruction of osseous structures. All voxels with signal intensity representative for bone are highlighted in blue. Since Hoffa's fat pad (1) and soft-tissue posterior to the distal femur (2) have similar signal intensity, they would be registered as part of the bony structures resulting in 3-D image artifacts. Consequently, disarticulation lines surrounding the bone are needed to exclude soft-tissue from 3-D display. Automatically defined disarticulation line around proximal tibia is shown (yellow, arrowheads).



Fig. 2C:
3-D MR surface reconstruction, posterior view. Osseous structures (white), menisci (magenta), anterior cruciate ligament (ACL) (yellow, arrowheads) and posterior cruciate ligament (PCL) (blue) are simultaneously shown. ACL is partially hidden by medial condyle in this projection. Origin and insertion of PCL is well shown; PCL is clearly posterior to ACL.



Fig. 2D:
3-D MR volume reconstruction, posterior view (same projection as in C). Due to the transparency effect, it is not certain whether the ACL (yellow, arrowheads) is located anterior or posterior to the PCL (blue) in the volume reconstruction. Volume reconstruction is limited when multiple overlapping objects are displayed.

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Pyramid Multicriterion Image Reconstruction from Projections

Lu Weixue and Wang Yuanmei

Institute of Biomedical Engineering, Zhejiang University,
PEOPLE'S REPUBLIC OF CHINA

1. INTRODUCTION

Digital reconstruction of image from projections has become a very active field of research and application in many different fields, especially in biology and medicine. Different techniques have been proposed for image reconstruction from projections. The most commonly used methods are transform methods, series expansion methods.

As image reconstruction from projections is a problem of estimation the original image from projection data. It is natural that the quality of the estimated image will depend upon the criterion used in estimation process.

Almost all CT Scanners today use the single criterion method to estimate the original image from projections. But actually the quality of an image usually involves several conflicting and noncommensurable criteria. It is obvious that different aspects of the image field must be considered during reconstruction.

In this paper we developed a multicriterion image reconstruction method with man-machine interaction as an aid in solving the multicriterion optimization problem.

To accelerate the reconstruction procedure a pyramid reconstruction approach has been explored.

2. MULTICRITERION IMAGE RECONSTRUCTION

There are several different criteria used in single

criterion reconstruction algorithm. Such as maximum entropy[2], least square error[1], nonuniformity and peakness[4]. It is natural that as a starting point we use the combination of these criteria to develop the multicriterion optimization method.

To reconstruct an image using multicriterion is equivalent to solving a vector optimization problem (VOP) of the form:

$$D1. \quad \min g(x) = (g_1(x), g_2(x), g_3(x))$$

where $g_1(x)$ is negative entropy function of the image, $g_2(x)$ is the sum of nonuniformity function and peakness function of the image, $g_3(x)$ is square error function of original test image and reconstruction. x is n -dimensional vector of decision variables x .

Upon satisfying certain conditions, the vector optimization problem D1 can be stated mathematically in term of optimal solutions of appropriate scalar optimization problem D2 (SOP) in the following manner:

$$D2. \quad \begin{array}{l} \text{minimize} \\ x \in X \end{array} \sum_{j=1}^3 w_j g_j(x) = w^T g(x)$$

$$\text{where } w_j > 0 \text{ and } \sum_{j=1}^3 w_j = 1$$

For a n -dimensional decision vector x the entropy function is:

$$g_1(x) = -\left(-\sum_{i=1}^n x_i \ln x_i\right) = \sum_{i=1}^n x_i \ln x_i$$

The sum of a nonuniformity function and peakness function is:

$$g_2(x) = \frac{1}{2} \alpha x^T S x + \frac{1}{2} x^T x$$

where matrix $\{S_{ij}\}_{n \times n}$ is called nonuniformity matrix[4], α is a constant chosen experimentally to yield the best reconstruction. The mean square error function is:

$$g_3(x) = \frac{1}{2} \beta (y - Ax)^T (y - Ax)$$

where β is a constant to be determined experimentally, y is a m -dimensional projections data vector, A is projection matrix.

We proposed an interactive method to solve D2 and the method can formalized as follow:

Step 1.

Set weight values w_1, w_2, w_3 , starting point x , constant α , β , and the ideal criterion values

Step 2

Typical iteration

$$x_j^{(k+1)} = \varphi(x^{(k)}) \quad j=1, 2, \dots, n, k=0.$$

Determine the two solution x^1 and x^2 ,

if $x^1 = x^2$ then problem is solved, goto step 4

if the decision-maker accept x^1 or x^2 as optimal then the problem is solved goto step 4. Otherwise $k=k+1$ goto step 3.

Step 3

Decision-maker questioning

Q1: "Do you consider the $g_1(x^k)$ satisfactory?

R1: "yes", goto Q2, "no" goto (2)

Q2: "Do you consider the $g_2(x^k)$ satisfactory?

R2: "yes", goto Q3, "no" goto (2)

Q3: "Do you consider the $g_3(x^k)$ satisfactory?

R3: "yes", goto (1), "no" goto (2)

Machine updating

(1) x^k is an optimal solution of D1, goto step 5

(2) Determine new weighting vector $w^k = (w_1^k, w_2^k, w_3^k)$
 $k=k+1$, goto step 2.

Step 4 Determine reconstructed image

$$(i, j) = x^k((n \times (i-1)) + j), \quad i=1, \dots, n, \quad j=1, \dots, n$$

Table 1 is the result of one of the interactive image reconstruction process. In this case we adjust the weighting vector w to make three criteria of the estimated image match the three ideal criterion values.

3. PYRAMID IMAGE RECONSTRUCTION APPROACH

To acceralate the reconstruction process a pyramid approach of reconstruction has been developed. Principle of the method is shown in Fig.1, i.e. the original image is deduced to a series of low resolution images (image pyramid). The image reconstruction was done on the lowest resolution level. Then the reconstructed image was expanded to a higher resolution level and modified by the data of the original Gaussian image of the corresponding level. This process is repeated until the highest resolution image is obtained.

4. SIMULATION RESULTS AND DISCUSSION

We use Shepp-Logan head model as the test image. 4 level pyramid structure is used. The original image is 114×114 pixels, then we obtain pyramid images of 58×58 , 30×30 , 16×16 pixels. The line integrals of object have been calculated according to the parallel ray geometry with 16×16 digitization. Hence, a test image vector is $x(256)$.

In order to compare different algorithms for singlr criterion optimization and vector optimization fairly, we have used three measures of performance. These measures emphasize different aspects of the image quality. d is normalized mean root squared error measure. r is normalized mean absolute error measure. e is worst case normalized error. The results of computer simulation using VAX-11/730 is shown in Table 2.

From Table 2 it is obvious that:

- (1) Multicriterion method has higher image quality than all single criterion methods.
- (2) Multicriterion method takes less time to reconstruct an image.
- (3) Pyramid approach of image reconstruction is effective.

Table 1

IDEAL CRITERIA		$\hat{g}_1=4.91$	$\hat{g}_2=.00476$	$\hat{g}_3=.001$		
ITERATION		i=0	i=1	i=2	i=3	i=4
WEIGHTS	w_1^i	0.2	0.25	0.4	0.36	
	w_2^i	0.3	0.25	0.2	0.22	
	w_3^i	0.5	0.5	0.2	0.42	
GOAL CRITERIA	$g_1(x^i)$	4.582	4.863	4.884	4.951	4.913
	$g_2(x^i)$	.0141	.00614	.00563	.00413	.00492
	$g_3(x^i)$	.00049	.00515	.00521	.00153	.00125
CRITERIA ERROR $\hat{g} - g$	$z_1(x^i)$		0.1%	.16%	.28%	.02%
	$z_2(x^i)$		43.6%	4.6%	2.6%	0.7%
	$z_3(x^i)$		207.6%	210.7%	21.3%	13.8%
ACCEPTED?			NO	NO	NO	YES

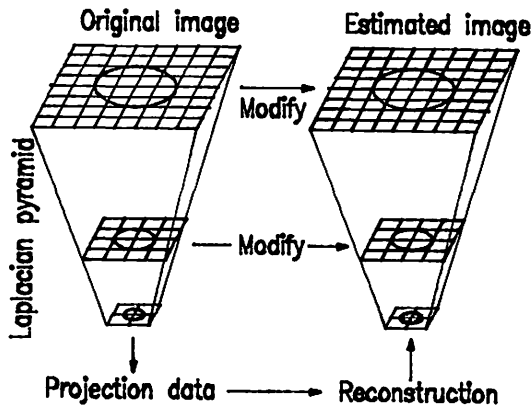


Fig. 1. Pyramid Image Reconstruction.

Table 2

ALGORITHMS	d	r	e	ITERATION NUMBER	ESTIMATION TIME,sec
MULTICRITERION ENTROPY OPTIMIZATION METHOD	.04990	.04829	.06718	4	152
MINERBO'S ENTROPY OPTIMIZATION [2]	.4728 .3843	.6123 .3607	.1270 .1720	5 16	256 848
GORDEN,et.al. MART [3]	.3475 .3212	.5032 .4731	.2310 .3210	5 20	252 1008
KASHYAP,et.al.[4] OPTIMIZATION METHOD	.2843 .2532	.4274 .4012	.2315 .1980	5 16	280 896

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Surface & Volumetric 3-D Reconstructions on an Engineering Workstation

Michael Gordon and Glen DeLoid

Department of Pharmacology, Kansas University School
of Medicine, Kansas City, KS and 3D Biomedical Imaging Inc.,
Shawnee Mission, KS

INTRODUCTION

In recent years, the engineering workstation has emerged as a separate category of computer system, residing between higher-end personal computers and minicomputers or mainframes. The CPU and graphics capabilities of these computers may provide the hardware bases for both surface and volume rendering approaches not only for engineering applications but also for use in the teaching and practice of medicine.

Background

A main distinguishing feature of the workstation is the availability of high performance graphics subsystems particularly optimized for 3D visualization. Additionally, these systems have a very large number of color memory planes and support displays having in excess of one million pixels. These graphics subsystems are connected to general purpose Unix-based host computers which in turn support the development and maintenance of large data sets associated with medical visualization. Within the workstation market there is range

of features and performance in the graphics systems; however, we will focus on the high-end graphics 3D workstation. The example system used in this article is the TurboSRX graphics system from Hewlett-Packard Company.

The development of high-performance graphics systems has been significantly motivated by the mechanical engineering market. Large manufacturing concerns that use sophisticated design approaches to develop and prototype components rely on 3D workstations. The availability of realistic computer graphic representation of components is thought to reduce the need for extensive prototyping and accordingly accelerates the design process.

In order to promote realism in design, surface or polygonal representations are used and rendered with specialized shading and lighting models. For the most efficient use of the engineers' time, interactivity is also crucial. Therefore, not only do the graphical representations have to be of the highest image quality, but also must be easily and rapidly rotated and translated. Specialized features including transparency, pan and zoom, and image blending enhance the users' ability to recognize complex 3D relationships. Understanding these complex spacial relationships are not only useful for the engineer working with complex mechanical objects, but also for the medical student and clinician in enhancing their appreciation of complex medical anatomy. As a result, the same graphical methods and features that are useful for the engineer may also be useful for members of the medical profession.

The type of solid model representation that is commonly associated with these design efforts is based on a surface model, one in which the hypothetical component is defined explicitly by a polygonal (triangular) mesh. Each triangle can be shaded, colored, and lighted. In the case of medical imaging, the particular anatomy is not a hypothetical structure, but is defined by a set of MRI or CT slices. These surface models can also be used in this environment, once the surface has been appropriately defined by thresholding or contouring.

The entire data set can also be viewed using volumetric rendering approaches that may not require explicit contour-based segmentation. Various volume rendering approaches can be implemented using specialized and more general purpose computing solutions.

Discussion

If 3D graphics workstations from major vendors provide the necessary computing environment for the medical user, some distinct advantages result. For example, because of competition between hardware vendors, price-performance points may be superior as contrasted to that offered by smaller suppliers. Additionally, this same competitive situation may result in earlier implementation of state-of-the art chip technology in support of both graphics and general purpose computation. These advantage affect both image quality and realism as well as interactivity.

Most of the emphasis in workstation design has focused on polygonal rendering

speed with associated features that promote image realism. The specialized geometry pipelines with their high-performance floating point transform engines and scan converters are now providing triangle rendering rates in excess of 100,000 per second. These capabilities support interactive surface polygonal anatomic representations. These graphical representations can be manipulated in real-time while not sacrificing access to graphical features such as transparency and complex directional, positional, and ambient lighting models. The availability of the polygonal vertex data allows cutting routines that reference the original voxel data set as a basis for the rendering of the cut surface. These cutting capabilities, which are also interactive, expanded the utility of 3D visualization by allowing internal explicit and sharp surface views. (1)

Volumetric visualization has provided extraordinary definition of medical volume data sets. Particularly useful has been the ability to represent objects that have no explicit boundary suitable for contouring. Multiple material models with translucency produce excellent images of such diffuse internal structures. Volume rendering can be performed on the same general purpose workstation as has been discussed above. One method relies on sampling a voxel subset that defines the material transition region. The voxel subset reduces the computational intensity to an extent that can be performed by the system CPU in a reasonable time. Another method which allows the use of the entire data set relies upon hardware assisted frame buffer compositing. (2)

Conclusions

For the graphics workstation to provide the basis for a complete solution in the medical environment, both surface and volume rendering need to be addressed. These methods are not competing methods but each offers special and unique approaches to 3D visualization. Contemporary 3D graphics workstations may have the necessary hardware to support both complimentary imaging modalities, leaving it up to the software developer to take advantage of those capabilities.

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Necessity of Window Functions in Filtered Backprojection Reconstruction – An Evaluation Based on Tumor Detectability Using an Optimal Linear Classifier

K.T. Daniel Yeung

Medical Image Processing Group, Department of Radiology,
University of Pennsylvania, Philadelphia, PA

1. Introduction

Computed tomography is a well established imaging modality. Commercial CT scanners typically use analytic reconstruction algorithms which are based on the filtered backprojection technique. The digital filter can be viewed as the application of a window function to regulate the intrinsic ramp frequency response [1]. There is a general agreement that a window function tuned to the imaging task will give a better reconstruction than one selected arbitrarily and that smoothing out the intrinsic ramp filter response by an additional window function is in general beneficial [2,3,4,5]. Assessment of algorithm performance are, traditionally, based on subjective evaluation, typically by visual examination and comparison of a few images and their reconstructions. The number of objective evaluation studies performed on the role of the window functions are rather limited [4,5,6,7]. There is also considerable confusion over the question of whether the window function is essential. Some believe that filtering during reconstruction can be replaced with appropriate post-reconstruction filtering. Others believe, however, that due to finite sampling, this is in fact not feasible in actual CT. Because of the lack of satisfactory objective measures for algorithm evaluation, this disagreement has not been convincingly resolved.

The Hotelling trace criterion (HTC), a figure of merit of class separability [8], has recently emerged as a promising performance measure for evaluating medical imaging systems [9]. Based on the HTC approach, we have developed a procedure for objective evaluation of image reconstruction algorithms [10]. The procedure assumed a tumor detection task (this is equivalent to a binary classification task for discriminating the tumor-present class from the tumor-absent class) and the evaluation was based on statistical data sets of phantom images simulating the human thorax, with tumors randomly placed in predefined tumor sites. The same procedure was adopted in this study. A training set (with 252 images) and two testing sets (each with 126 images) and the necessary data were constructed to evaluate how the choice of the window function and the interpolation affect the performance of the filtered backprojection reconstruction algorithm. The algorithm performance was quantified by how well the optimal linear classifier could perform the tumor detection task, using optimal linear features derived from images reconstructed by

the algorithm. Selected post-reconstruction filterings were also performed on those reconstructions that were based on the ramp filter and were evaluated as above. This latter study was designed to answer the question of whether the window function is essential in the filtered backprojection reconstruction algorithm. We report our experimental results and findings in this paper.

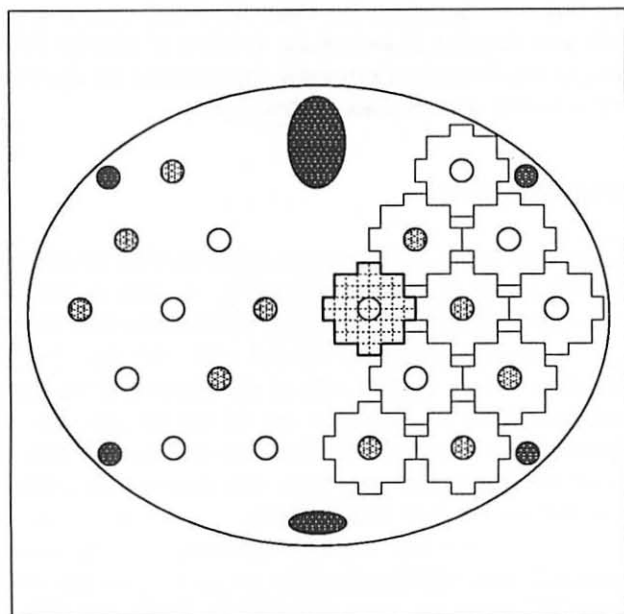
2. Data and Methods

The data sets used in the reconstruction and evaluation studies were based on a phantom image simulating the human thorax (Fig. 1), with an image size of 53×53 pixels. Bony structures including the sternum, vertebra and four ribs were simulated with ellipses and circles of appropriate size, all with a density value of 0.4. Twenty potential tumor sites, ten on the left side of the thorax and ten symmetrically on the right, were also defined. Five sites out of ten on one side were randomly selected and placed with a tumor. The five sites on the other side defined by the mirror images of the unoccupied sites were also placed with a tumor. The tumor was assigned a density value of 0.205, versus a value of 0.2 for normal tissues. Altogether, 252 images, each with a unique combination of the ten occupied tumor sites, were generated. Two additional sample sets, each with 126 images randomly selected from the 252 image set, were also defined. Projection data of these image data with parallel geometry were generated using SNARK89 [11], with 180 views equally spaced over 180 degrees and a ray spacing of 1.0 pixel. Poisson noise were independently added to these projection data to generate three noise levels with averages of 1000, 2000 and 4000 photons per ray.

The above procedure was repeated to generate a similar collection of projection data except with a finer ray spacing of 0.5 pixel. The three noise levels were adjusted to have, respectively, averages of 500, 1000 and 2000 photons per ray to compensate for the doubling of the number of rays in the new projection data.

Based on the above projection data, images were reconstructed using the filtered backprojection (also referred to as convolution) algorithm with the choice of linear interpolation and one of the following filters: the ramp, Shepp and Logan, cosine (ramp with a cosine window) and Hamming (ramp with a Hamming window) [1,12,13,14]. Zero order (nearest neighbor) interpolation was also used for the ramp and the cosine filters. All of the above filters were defined with a cutoff frequency equal to the Nyquist frequency of sampling with ray spacing of 1.0 pixel.

To test whether filtering by an additional window function during reconstruction is the same as post-reconstruction filtering by the same window function, the following experiments were performed. The two dimensional discrete Fourier transform was applied to images reconstructed using the ramp filter. The Fourier coefficients were filtered by the frequency response of the cosine window and the inverse Fourier transform was then applied to generate the post-reconstruction filtered images. Zero padding was used in the discrete Fourier transform to minimize inter-period interferences. These images were then compared with those reconstructed using the cosine filter.



	density
soft tissue	0.2
○ unoccupied tumor site	0.2
⊗ occupied tumor site	0.205
● bony structures	0.4

Figure 1 A thorax phantom with the non-overlapping sub-images illustrated. Each sub-image is a 44 pixel region centrally enclosing a potential tumor site.

The above reconstructed images were evaluated using a tumor detection task and the performance of the optimal linear classifier was used as the performance index. To generate a two class data set for our binary classification task (discriminating the presence or the absence of a tumor), 20 non-overlapping subimages, each defined by a 44 pixel region around a potential tumor site (see Fig. 1), were extracted from each reconstructed image. The tumor-present (tumor-absent) class encompassed all those subimages where a tumor was present (absent).

For each setting of imaging parameters (a given choice of reconstruction filter, interpolation, projection data sampling rate and noise level), reconstructed images of the 252 image set (which formed a two class data set with 1260 objects each) was used as the training set to determine the optimal linear feature operator. For binary classification, only one feature was needed [8]. This optimal feature operator, which we obtained using a multidimensional biased random search technique [15], thus

defined a single feature which maximized the class separability measure between the two object classes. This optimal class separability measure (the HTC) was adopted as a figure of merit for quantifying the performance of the reconstruction algorithm. Another figure of merit that we adopted was the area under the ROC curve; the ROC curve was determined by the maximum likelihood estimate [16], using output of the optimal linear feature operator as the decision variable.

The optimal linear feature operators, one for each setting of imaging parameters, were then applied correspondingly to the two testing sets to determine the two figures of merit for quantifying the performance of the given algorithm. The same evaluation procedure was applied to the post-reconstruction filtered images. To investigate whether significant errors were introduced in the post-reconstruction filtering process merely as a result of finite implementation, post-reconstruction filtered images and the pre-reconstruction filtered images based on some form of idealized projection data were compared. The projection data chosen for this study was the noiseless data with the finer ray spacing of 0.5 pixel.

3. Experimental Results

The algorithm performance given by the HTC measure for various filter functions and the two choices of interpolation are tabulated in Tables 1 and 2. Results in Table 1 are based on the projection data sets with ray spacing of 1.0 pixel whereas those in Table 2 are with ray spacing of 0.5 pixel. All the three noise levels in each case are shown. In the tables, the first letter of the two-letter code denotes the filter function used with R for ramp, S for Shepp and Logan, C for cosine and H for Hamming. The second letter denotes the interpolation used with Z for zero order and L for linear.

Table 1 The HTC performance measure for various choices of filter and interpolation using the projection data sets with ray spacing of 1.0 pixel.

Noise Level (spacing=1.0)		RZ	RL	SL	CL	HL
1000	Training	0.101	0.140	0.141	0.142	0.143
	Testing 1	0.106	0.139	0.141	0.148	0.150
	Testing 2	0.103	0.148	0.150	0.149	0.148
2000	Training	0.211	0.285	0.288	0.298	0.305
	Testing 1	0.181	0.249	0.254	0.263	0.266
	Testing 2	0.187	0.267	0.270	0.272	0.273
4000	Training	0.419	0.573	0.582	0.610	0.619
	Testing 1	0.366	0.475	0.486	0.512	0.524
	Testing 2	0.366	0.505	0.515	0.543	0.547

Table 2 The HTC performance measure for various choices of filter and interpolation using the projection data sets with ray spacing of 0.5 pixel.

Noise Level (spacing=0.5)		RZ	RL	SL	CL
500	Training	0.139	0.159	0.160	0.161
	Testing 1	0.106	0.121	0.121	0.130
	Testing 2	0.096	0.112	0.113	0.118
1000	Training	0.234	0.282	0.284	0.286
	Testing 1	0.232	0.277	0.278	0.277
	Testing 2	0.216	0.263	0.263	0.265
2000	Training	0.483	0.597	0.601	0.608
	Testing 1	0.475	0.599	0.601	0.602
	Testing 2	0.479	0.602	0.606	0.605

In Tables 3 and 4, both figures of merit, the HTC and the area under the ROC curve, are tabulated for the post-reconstruction filtered images based on the projection data sets of ray spacing of 1.0 pixel and 0.5 pixel respectively. A third letter C is added to denote the cosine window function used for the post-reconstruction filtering. The two performance measures for the ramp and cosine filters are also tabulated along side to ease comparison with those using post-reconstruction filtering. Only the two lower noise levels in each case are shown.

In Table 5, we tabulated a few metrics derived from the following reconstructed images: ramp with zero order interpolation, the former plus post-reconstruction filtering with the cosine window, cosine with zero order interpolation, ramp with linear interpolation, the former plus post-reconstruction filtering with the cosine window and the cosine with linear interpolation. All these reconstructions are based on one of the phantom and the noiseless projection data with the ray spacing of 0.5 pixel. The metrics for the phantom itself are also tabulated. The metrics *distance* and *relative error* [17] are commonly referred to as the normalized root mean square distance and the mean absolute distance, both with respect to the phantom image.

Table 3 The HTC and A_z performance measures for the ramp filter, cosine filter and the ramp with post-reconstruction using the cosine window, for the projection data with ray spacing of 1.0 pixel.

Noise Level (spacing=1.0)			RZ	CZ	RZC	RL	CL	RLC
2000	Training	HTC	0.211	0.270	0.219	0.285	0.298	0.289
		A_z	0.741 ± 0.007	0.769 ± 0.007	0.746 ± 0.007	0.775 ± 0.006	0.779 ± 0.006	0.777 ± 0.006
	Testing 1	HTC	0.181	0.240	0.187	0.249	0.263	0.252
		A_z	0.729 ± 0.01	0.755 ± 0.009	0.733 ± 0.01	0.763 ± 0.009	0.771 ± 0.009	0.765 ± 0.009
	Testing 2	HTC	0.187	0.249	0.197	0.267	0.272	0.267
		A_z	0.730 ± 0.01	0.760 ± 0.009	0.736 ± 0.01	0.767 ± 0.009	0.770 ± 0.009	0.765 ± 0.009
4000	Training	HTC	0.419	0.550	0.432	0.573	0.610	0.587
		A_z	0.820 ± 0.006	0.853 ± 0.005	0.825 ± 0.006	0.858 ± 0.005	0.863 ± 0.005	0.861 ± 0.005
	Testing 1	HTC	0.366	0.449	0.382	0.475	0.512	0.489
		A_z	0.803 ± 0.009	0.829 ± 0.008	0.808 ± 0.008	0.835 ± 0.008	0.845 ± 0.008	0.837 ± 0.008
	Testing 2	HTC	0.366	0.497	0.394	0.505	0.543	0.522
		A_z	0.802 ± 0.009	0.841 ± 0.008	0.812 ± 0.008	0.843 ± 0.008	0.852 ± 0.007	0.848 ± 0.008

Table 4 The HTC and A_z performance measures for the ramp filter, cosine filter and the ramp with post-reconstruction using the cosine window, for the projection data with ray spacing of 0.5 pixel.

Noise Level (spacing=0.5)			RZ	CZ	RZC	RL	CL	RLC
1000	Training	HTC	0.234	0.274	0.236	0.282	0.286	0.287
		A_z	0.753 ± 0.007	0.770 ± 0.007	0.754 ± 0.007	0.774 ± 0.006	0.774 ± 0.006	0.775 ± 0.006
	Testing 1	HTC	0.232	0.270	0.229	0.277	0.277	0.276
		A_z	0.753 ± 0.01	0.770 ± 0.009	0.752 ± 0.01	0.773 ± 0.009	0.770 ± 0.009	0.772 ± 0.009
	Testing 2	HTC	0.216	0.250	0.209	0.263	0.265	0.264
		A_z	0.746 ± 0.01	0.763 ± 0.009	0.740 ± 0.01	0.766 ± 0.009	0.764 ± 0.009	0.768 ± 0.009
2000	Training	HTC	0.483	0.564	0.487	0.597	0.608	0.608
		A_z	0.836 ± 0.006	0.856 ± 0.005	0.839 ± 0.006	0.862 ± 0.005	0.864 ± 0.005	0.864 ± 0.005
	Testing 1	HTC	0.475	0.557	0.462	0.599	0.602	0.601
		A_z	0.836 ± 0.008	0.853 ± 0.007	0.832 ± 0.008	0.863 ± 0.007	0.865 ± 0.007	0.864 ± 0.007
	Testing 2	HTC	0.479	0.540	0.459	0.602	0.605	0.602
		A_z	0.838 ± 0.008	0.851 ± 0.008	0.831 ± 0.008	0.866 ± 0.007	0.867 ± 0.007	0.866 ± 0.007

Table 5 Metrics for selected reconstructions of a single phantom using noiseless projection data with ray spacing of 0.5 pixel.

Metric	Phantom	RZ	CZ	RZC	RL	CL	RLC
average	0.1155	0.1155	0.1155	0.1155	0.1155	0.1155	0.1155
distance	0.0	0.0696	0.0888	0.0887	0.0563	0.0894	0.0896
relative error	0.0	0.0423	0.0344	0.0335	0.0325	0.0299	0.0300
variance	0.0107	0.0109	0.0104	0.0104	0.0109	0.0104	0.0104

4. Discussion

Some interesting results can be observed from Tables 1 and 2. For a given reconstruction filter, the algorithm performance given by the HTC measure more or less doubled as the photon count in the projection data doubled. This is consistent with the fact that the HTC measure is inversely proportional to the variance of the reconstructed pixel densities [9]. The algorithm performance is seen to increase with the smoothness of the reconstruction filter (filters in the tables were arranged with increasing smoothness from left to right). Improvements in lesion detectability with smoother filters have also been reported elsewhere [4,5]. For our data, a filter smoother than the Hamming filter did not seem to have as good a performance.

A rather interesting finding is that the most dramatic improvement in algorithm performance occurred with the choice of the interpolation. Using the area under the ROC curve (A_z) and its error estimate ($\sigma(A_z)$) given in Table 3, the use of linear interpolation with the ramp filter is seen to provide a very significant improvement (about $4.0 \sigma(A_z)$) in algorithm performance over that with zero order interpolation. As a comparison, when linear interpolation was used, the performance achieved with the rather smooth cosine filter is only one standard deviation better than that with the intrinsic ramp filter. For the results based on the finer sampled projection data (Table 4), using linear versus zero order interpolation with the ramp filter results in a lesser but still rather significant improvement (about $3.0 \sigma(A_z)$), whereas the choice of filters did not seem to matter much when linear interpolation was used. Evaluation based on the HTC measure, though we do not have an error estimate, also leads to similar conclusion.

Even though the results above point to the choice of a smooth filter and linear interpolation and the fact that a proper choice results in a significant improvement in algorithm performance, we must emphasize that the relative performance of various reconstruction filters also depend on other imaging parameters such as the sampling rate and noise level in the projection data, the objects to be reconstructed, the imaging task to be performed, etc.

The results given in Tables 3 and 4 served to answer the question of whether pre-reconstruction filtering can be equivalently performed with corresponding post-reconstruction filtering. The cosine filter with both choices of interpolation was chosen for this study. For the results based on the projection data sampled at 1.0 pixel spacing (Table 3), the cosine filter is seen to provide significant improvement over the ramp filter for both zero order and linear interpolation (respectively by $3.0 \sigma(A_z)$ and $1.0 \sigma(A_z)$). Post-reconstruction filtering with the cosine window on images reconstructed by the ramp filter is seen to provide slight improvement on both performance measures (by about 0.5 standard deviation for the A_z measure) for both choices of interpolation. For the case of linear interpolation, since the performance of the cosine filter is only one standard deviation better than that of the ramp, we can not say with statistical significance that there is a genuine difference between pre-reconstruction filtering and corresponding post-reconstruction filtering. For the case with zero order interpolation, however, one

can see that pre-reconstruction filtering using the cosine filter is significantly better than the post-reconstruction filtering using the cosine window.

For the results based on the finer sampled projection data (Table 4), there is no significant difference in performance between the ramp filter, the ramp filter with post-reconstruction filtering using the cosine window and the cosine filter, for the case of linear interpolation. For zero order interpolation, the cosine filter still performed significantly better than the ramp filter (by about $2.0 \sigma(A_z)$). Post-reconstruction filtering on the reconstructions by the ramp filter seems to result in a slightly poorer, though not significant, performance. Once again, the pre-reconstruction filtering using the cosine filter is significantly better than the post-reconstruction filtering using the cosine window.

Aliasing artifacts [18], to which sharp reconstruction filters are more prone, are errors that we believe could not be effectively removed by post-reconstruction filtering. This is believed to contribute, at least in part, to the observed poorer performance associated with the post-reconstruction filtered images. The above arguments would lead to an expectation that post-reconstruction filtering for the finer sampled projection data with 0.5 pixel spacing (with less aliasing) would result in more improvement than for the data with 1.0 pixel spacing, given all other imaging parameters the same. The above observed results seemed to fail our expectation. This latter conclusion is not necessarily true due to a design flaw in the experiments. Even though the experiments were set up with the aim that the projection data sampling rate was the only variable, a closer look revealed a subtle difference in the overall frequency response of the filter used for the two data sets. This arose because the frequency response resulted from interpolation actually depended on the Nyquist sampling frequency. The response associated with zero order interpolation for the finer sampled data as a result was much sharper. This could have led to what we have observed.

A natural question that arises is whether the observed significant difference between pre-reconstruction filtering and corresponding post-reconstruction filtering is not merely due to errors introduced by the finite implementation of the post-reconstruction filtering process. The results given in Table 5 addressed this issue. The table listed a number of metrics derived from relevant reconstructed images (and the phantom) of a single phantom based on noiseless projection data with the finer spacing of 0.5 pixel (a form of idealized data). For both cases of interpolation, one can easily see quite a difference in the metrics between that of the ramp and the cosine filter. For the case of linear interpolation, the post-reconstruction filtering with the cosine window resulted in metrics more or less identical to those using the cosine reconstruction filter. That is to say, the finite implementation of the post-reconstruction filtering process did not result in a significant error. For the case of zero order interpolation, the same is true for most metrics except for the relative error measure which amounts to say, for the given data, that the post-reconstruction filtered image still differs from that reconstructed from the cosine filter. This could well happen given the relative sharp response of the ramp filter with zero order interpolation.

In summary, we have shown that based on a tumor detection task and an objective evaluation using the optimal linear classifier, window functions are both necessary and essential for the filtered backprojection reconstruction algorithm. A proper choice of the reconstruction filter can result in a significant improvement in algorithm performance and that filtering effected by the window function associated with the filter can not always be equivalently replaced with post-reconstruction filtering using the same window function.

Acknowledgements

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A Numerical Two – Alternative – Forced – Choice (2AFC) Evaluation of Imaging Methods

Gabor T. Herman and Dewey Odhner

Department of Radiology, Hospital of the University of Pennsylvania,
Philadelphia, PA

1. Introduction. The two-alternative-forced-choice (2AFC) approach to evaluating the comparative quality of two or more imaging methods consists of presenting observers with pairs of images, exactly one of which is known to have a signal (tumor, abnormality, etc.) in it. The observer selects one as signal containing. The respective percentages of correct hits are used as figures-of-merit (FOM's) of the imaging systems. Under appropriate conditions, this FOM approximates the area under the receiver-operating-characteristic (ROC) graph [1].

To avoid the time and expense of using human observers in a 2AFC study, one can perform a numerical version of the same. Here one associates a computable abnormality index with the images and selects the image with the higher abnormality index [2].

We designed such a numerical 2AFC experiment to evaluate the comparative performance of image reconstruction methods for detecting increased uptake in Positron Emission Tomography (PET). Mathematically described phantoms approximating structures in the brain at various transaxial levels were used. The structures are symmetrical with respect to the midline. For each pair of symmetrical structures in the phantoms, one of the pair was randomly selected to have a higher uptake than the other. A total of 104 phantoms were generated containing 856 pairs of structures. The data collection (including noise) of a PET scanner was simulated and each of the phantoms was reconstructed by various image reconstruction methods, which were then evaluated using numerical 2AFC, by selecting that structure of a pair which has the higher total activity in it in the reconstructed image.

We report on our experiments comparing the classical convolution (or filtered backprojection) method with expectation maximization (EM) algo-

rithms both for maximization of likelihood (ML) and for maximum *a posteriori* probability (MAP) estimation. In addition to reporting on the results of the 2AFC evaluation (a decision task) we also report on the results of a distance-measure evaluation (an estimation task).

2. Data Generation and Evaluation Methodologies. In order to make our experiments realistic from the point of view of clinical imaging tasks, we used a computerized overlay atlas based on average anatomy [3]. This atlas consists of 26 overlays each corresponding to a transaxial slice of the brain. Neuroanatomic structures are represented by ellipses and rectangles at the appropriate locations; they are symmetrical with respect to the midline. We made use of this symmetry to set up our 2AFC experiment as follows.

We created mathematical phantoms in which (in arbitrary units) the activity in the brain background is 1.00 and in the neuroanatomic structures it is 1.95 or 2.00. For each pair of symmetric structures a random number generator chooses exactly one of the pair to have activity 2.00. Thus the task is to decide, based on the reconstructions, which one of the pair of structures has the higher activity. The top left image in Fig. 1 shows one such phantom.

We generated images and projection data of these phantoms using SNARK89 [4]. In generating the projection data we assumed a ring of 300 detectors with each detector in coincidence with 101 detectors opposite it. (In SNARK89 terminology, we have a divergent ray geometry with 300 views and 101 rays per view.) Poisson noise was introduced into the measurements on the basis of a total 3×10^6 photons collected per slice (averaging approximately 100 photons per SNARK89 ray). The resulting ray sums were further deteriorated by a 10% multiplicative Gaussian noise, to take care of other sources of error besides photon statistics.

The set of 26 overlays was reused four times; the sides of elevated activity and the noise in the data were chosen independently for the four data sets. Thus a total of 104 phantoms (and their projection data) were generated; they contain a total of 856 pairs of symmetric structures.

The FOM of a reconstruction method provided by 2AFC for such a data set is defined as follows. For each structure we define the *abnormality index* in the reconstruction to be the sum of reconstructed pixel values for those pixels whose centers are within that structure in the phantom. A pair of symmetric structures provides us with a *hit*, if the abnormality index

in the reconstruction is higher for that structure in the pair for which the activity is higher in the phantom. The FOM is the ratio of hits to the total number of pairs in the data set.

Since most image reconstruction methods have some free parameters in them, it is appropriate prior to evaluation to train the method for a particular task [2]. For this reason, we designated one of the four data sets (each consisting of 26 phantoms and their projection data) to be a training set and the other three to be testing sets. The free parameters were chosen so that they give the highest possible FOM on the training set, and then the methods were evaluated with these parameters fixed on the (statistically independent) testing sets.

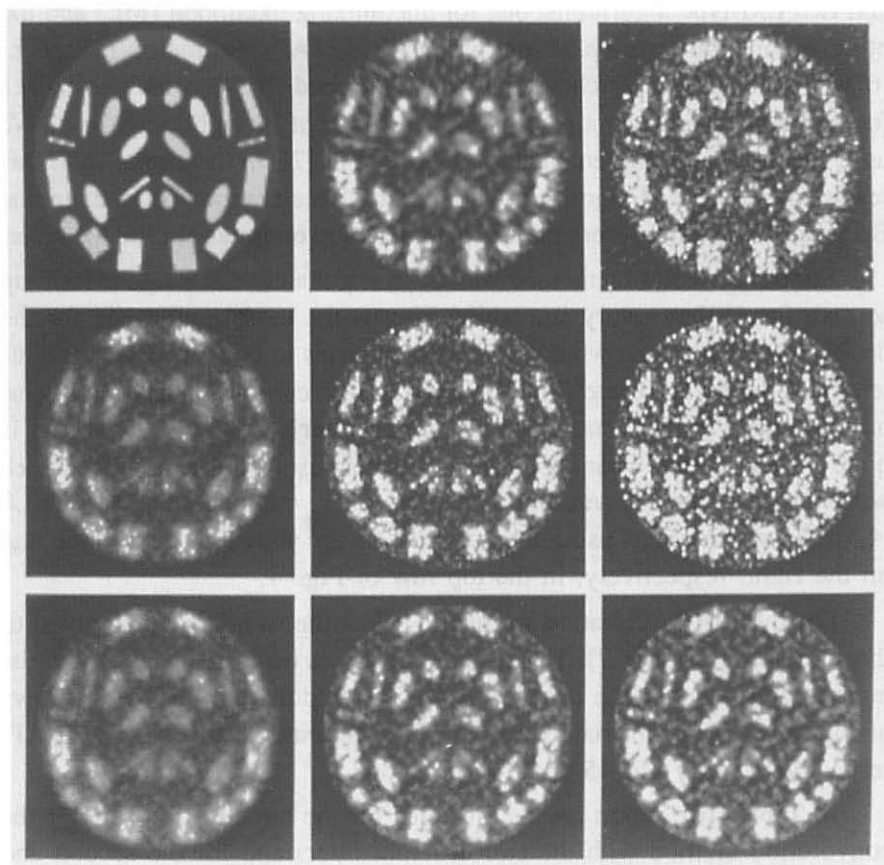


Figure 1. One of the phantoms and its reconstructions.

In addition, we decided to evaluate the performance of the reconstruction methods from another point of view: namely, on the basis of their ability to estimate the total uptake in the neuroanatomic structures. For this we used the so called clipped normalized distance provided by SNARK89 [4]. Briefly, for this measure both the phantom and reconstruction are clipped, by setting pixel values which are less than (in our case) 1.65 to 1.65 and pixel values which are more than (in our case) 2.05 to 2.05. After this a normalized root mean square distance between the clipped reconstruction and clipped phantom is calculated. The clipping insures that only the accuracy within neuroanatomic structures contributes to the distance measure.

3. Experimental Results. The methods that we compared were the convolution (also known as filtered backprojection) method (see, e.g., [5]) and two EM-type algorithms, one for maximizing likelihood (ML) and the other for maximum *a posteriori* probability (MAP) estimation (see, e.g., [6]). For the latter we chose the prior described in [7], which penalizes for differences between a pixel and the average of its eight neighbors. We used the computer implementation described in [7]; in the case of ML this results in a pure EM algorithm without any "acceleration" or other tricks. Because of this, there were no free parameters to optimize for the ML case.

For the convolution method we had to select a filter. Using the training set, we found that a very smoothing filter is the most appropriate for the decision task; it is one which sets all frequencies to be zero beyond eight-tenths of the Nyquist rate (in SNARK89 terms: cutoff=0.8) and otherwise has the shape of the generalized Hamming filter with $\alpha=0.5$ [5]. This is quite different from what has been found most useful for x-ray CT, which would typically be a generalized Hamming filter with $\alpha=0.8$ and cutoff=1.0 [4,5]. Reconstructions using these two filters are shown in the middle and on the right, respectively, in the top row of Fig. 1.

For the MAP estimation we had to select the weight γ to be given to the smoothing prior [6,7]. Using the training set we found $\gamma=10$ to be the most appropriate for the decision task. The middle and the bottom rows of Fig. 1 show reconstructions by the EM algorithms, for ML and MAP, respectively, after 15, 45 and 145 iterations.

In Table I we report on the hit ratios for the three testing sets for the convolution method with the two different filters and for the second and the twentieth iterations of the two EM algorithms. In Fig. 2 we report

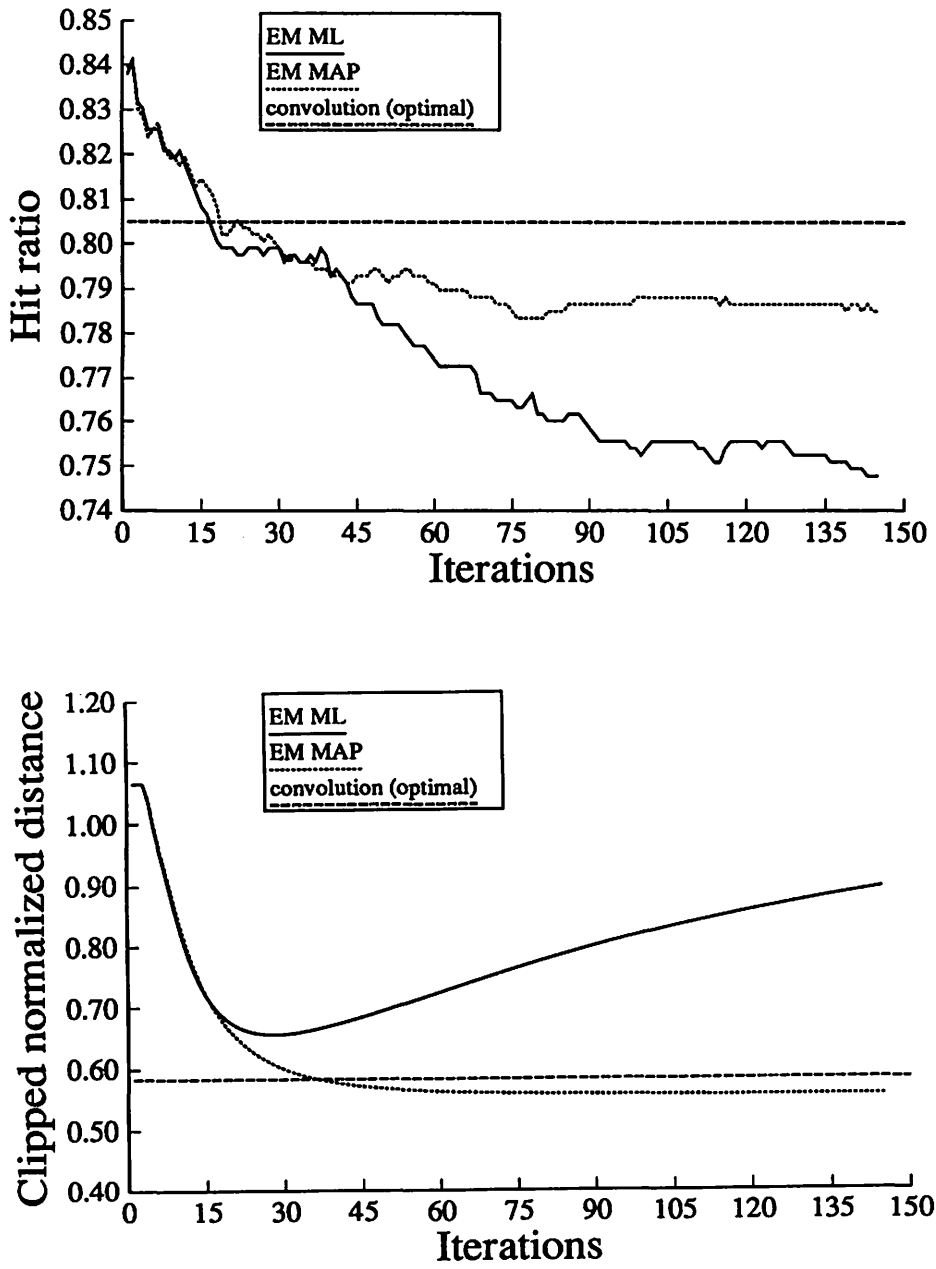


Figure 2. The averages over the three testing sets of the hit ratios (top) and clipped normalized distances (bottom).

on the averages (over the three testing sets) of the hit ratios and of the clipped normalized distances.

Testing Set Number	1	2	3
convolution (optimal)	.762	.822	.832
convolution ($\alpha=.8$, cutoff=1)	.715	.785	.790
both EM's (iteration 2)	.822	.869	.832
EM (ML, iteration 20)	.766	.832	.799
EM (MAP, iteration 20)	.771	.832	.804

Table 1. Hit ratios for the testing sets.

4. Discussion. Our results can be summarized as follows.

1. Early iterates (up to about fifteen) of the two EM algorithms perform very similarly for both tasks. With increasing number of iterations the performance of ML optimization deteriorates relative to MAP estimation.
2. For the 2AFC (decision) task, the second iterate of the EM algorithms was the best and it outperformed the (task-optimized) convolution method. However, the performance of both EM algorithms deteriorates with increasing number of iterations and gets to be worse than the (task-optimized) convolution method after the twenty-fifth iteration.
3. For the estimation task, the two EM algorithms perform quite differently. For ML, the performance improves until the twenty-eighth iteration, after which it gets worse, never reaching the performance of the convolution method. For MAP, the performance improvement is monotonic, with performance becoming better than that of the convolution method after the fortieth iteration.

Note that the performance of the methods is very task-dependent. The second iteration of EM is better than convolution for the decision task, but is worse than convolution for the estimation task. The reverse is true for the fortieth iteration of the EM algorithm for MAP compared with convolution. Hence, while numerical 2AFC is a perfectly reasonable approach if we are evaluating the comparative performance of two imaging methods for a decision task, one has to be careful not to jump to conclusions regarding the relative performance of the two methods for another task, especially for an estimation task.

For reasons of space we do not provide here a discussion of the statistical significance of our results; we refer the reader to [8].

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Problems in Three-Dimensional Reconstruction of Abdominal CT Scans

R.-W. Kenn^o, R.M. Huber^o, D. Wilker^{*}, J.R. Izbicki^{*}, J. Ohman[^], K.J. Pfeifer^o

^oRöntgenabteilungen der ^{*}Chirurgischen Klinik und der Medizinischen Klinik Innenstadt der Universität München

[^]Picker Inc., Highland Heights, Ohio

1. Purpose

Modern surgery requires exact planning. The radiologist not only has to state the diagnosis, but also to provide a maximum of spatial information for the surgeon. In order to acquire an optimal spatial perception, a variety of mapping modalities is at hand, including US, CT, MRI, and DSA. 3D information is contained in any set of tomographic slices. All the information is primarily gathered by the radiologist and, mentally built into a spatial image. Nevertheless it is difficult to explain spatial relation to a large forum (conferences) on the basis of cut - modality images. As every listener has to build up the image in his mind from the information of transversal cut modalities and additive modalities (DSA), the results often vary individually. The optimal way to present the spatial information would be to present a model of the relevant anatomical objects (organs, lesions, vessels, bones a.s.o.). As the construction of models is very time - consuming, the 3D display on monitors with shading characteristics is applied. This system is well established in bone surgery (spine, pelvis). It has, up to now, seldom been applied to the abdominal structures, which have a no less complicated spatial relation. Choosing the liver with focal lesion as an example, we want to show a few of the problems arising from 3D reconstruction of abdominal structures.

2. Method and Material

Prior to surgery of primary or secondary focal liver lesions we routinely perform a liver CT - scan (Picker 1200 Expert) under transarterial portographic (CTAP) conditions. Contrast media is selectively injected into the SMA. This study modification has proved to optimize lesion detectability by maximizing lesion / parenchyma contrast difference. At the same time, the portal venous system is maximally enhanced.

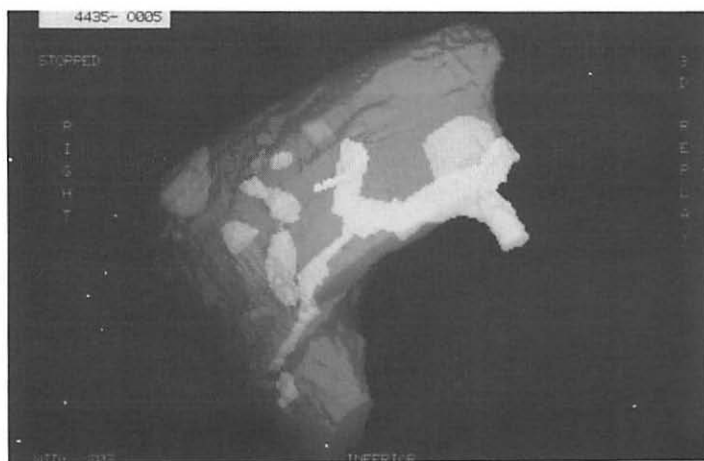


Fig. 1. Transparency 3D image of the liver. The liver is translucent so that the portal branches and the focal lesion can be seen within the liver

Analysing 12 of these CT scans, we reconstructed 3D images of the liver. In order to reconstruct the 3D appearance of an object of interest it is necessary to determine the pixels of the object in the slices. There are three possible ways to collect the pixels. Defining a range of HU will define the pixels not only of the chosen organ but also of several other areas of the slices. To avoid marking of unwanted pixels, the autocontour procedure is administered. With this procedure, a certain threshold, depending on the densities of the object, is chosen. Setting the cursor in the CT-slice and starting the procedure, the computer seeks in a straight line to the left of the cursor until she finds a pixel with a HU of the threshold value or higher. In a clockwise direction, the computer constructs a border between pixels with HU higher and HU lower than the threshold. By this means, even an

inhomogenous structure can be collected as long as a border can be defined. In some cases it is necessary to edit manually, i.e. to "draw" a part of the contour by hand. Once the border surrounds the chosen structures, all pixels inside are "collected" for reconstruction.

This procedure is repeated in all slices and for all objects, where objects embedded inside another object have to be defined first, otherwise they would be added to the surrounding object (i.e. liver metastasis).

We reconstruct three objects: the portal system, the tumors, and the liver parenchyma. These objects are then displayed simultaneously as a so called "transparency", for some objects are transparent in order to visualise the objects within (fig. 1).

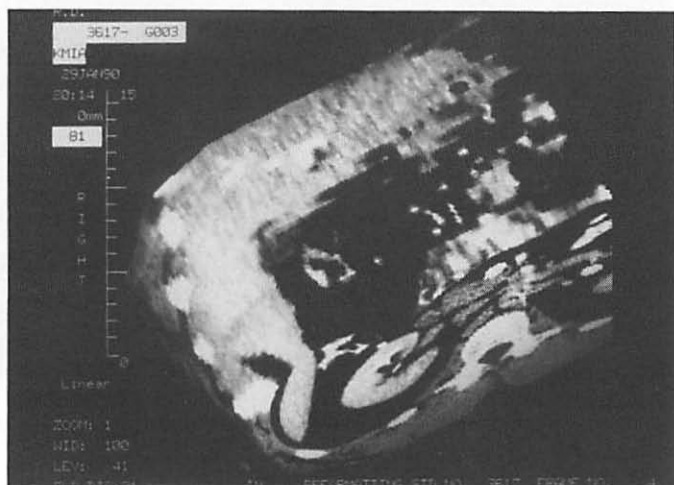


Fig. 2. The region of the liver is reconstructed as a block. The CT values are added to the surface. The liver is seen from anterior and left, from inferior the kidney and the spine can be seen clearly.

A second method to achieve a 3D image, the so called block display, is to collect a block of data. This means to collect the data without special marking of objects. The whole block is reconstructed and the HU are shown on the surface of the block (fig. 2). The block can be cut in any plane, rotated and combined with the reconstruction of single objects (fig. 3).

To show the object spinning or tumbling on the monitor is, in a certain way, still another 3D modality. This "3D - movie" can be performed with a transparency as well as with block data.

The reconstructed images and the 3D - movies are evaluated in regard of best spatial information, in relation to transversal CT scans and DSA. The evaluation is performed by 1 radiologist, 1 radiology resident, 3 surgeons, 2 surgery residents and 2 medical students. Each study is graded from 1 (very good spatial information) to 6 (no spatial information). The surgeons were asked additionally to value the 3D display, if it was necessary for the operation (grade 1) or did not help at all in planning and performing the operation (grade 6). After figuring the average grade for each modality for every test reader the grades were normated for comparison.

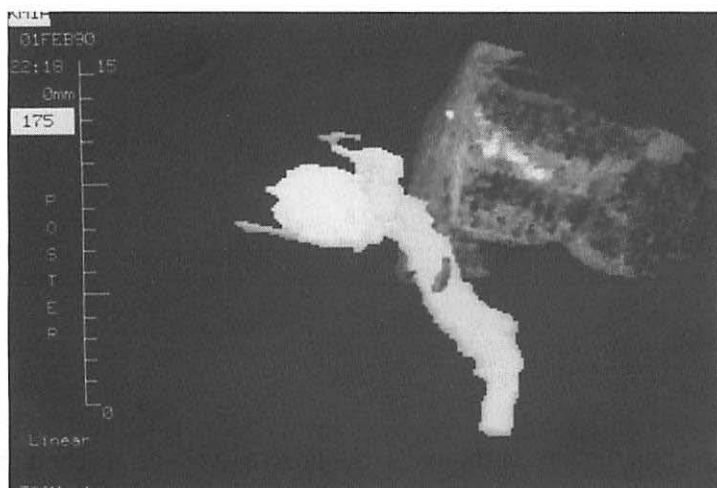


Fig. 3. Transparency display and block display are combined. The right lobe of the liver is cut off, the left lobe is displayed as block with CT values added to the surface. Tumor and portal vein with branches are added as distinct objects.

3. Results

To define an object of interest, manual contouring does not create reproduceable results. Autocontouring does not determine the exact borders in most cases, but is reproduceable. Autocontouring is sufficient to determine the boundaries of most focal liver lesions and of the portal system when performing CTPA. A combination of manual editing and autocontouring shows best results to determine the liver boundaries. None of our studies could be reconstructed without manual editing.

The average spatial information value of the different modalities as evaluated by the test readers is shown in the following table (grades already normated):

Test reader		DSA	CT	3D Image	3D Movie	3D Value
Surgeon	1	4.8	1.9	2.7	2.5	—
Surgeon	2	4.8	3.0	2.3	1.7	3.4
Surgeon	3	5.2	3.0	2.3	2.2	4.4
Surg. Res.	1	4.3	2.7	2.8	2.3	1.5
Surg. Res.	2	4.7	3.1	2.6	2.4	2.3
Radiologist		5.0	2.8	2.4	1.9	—
Rad. Res.		4.2	2.3	3.0	2.7	—
Med. Stud	1	4.6	2.9	2.2	2.2	—
Med. Stud.	2	4.5	2.4	2.8	2.4	—

4. Discussion

The 3D reconstruction of bone is by now a well established part of preoperative planning in the field of the spine, pelvis, and cranio - facial disorders. Because of the high contrast differences it is rather easy to determine the object margins and in most cases this can be performed automatically with a high degree of reproducibility.

The average HU of the anatomical objects in the abdomen vary significantly, but in most instances have a wide range and because of this fact overlap. Just choosing certain density levels and/or ranges is not sufficient to determine the anatomical structures. Autocontour procedures do help to increase the reproducibility, but in all our cases, manual editing was essential. Statistical boundary analysis and object recognition should be introduced for totally automated, reproducible contour finding.

As the clinical diagnosis is established by other modalities, the 3D image does not need to be highly reproducible as long as only spatial relations have to be shown. Actually the radiologist, editing the slices for reconstruction, already has to know what the result has to look like.

A basic problem in 3D development is the varying acceptance by the clinicians. Most surgeons, after a moment of enthusiasm, continue preferring the cut slice display they are used to. If the clinician is not that much used to reading CT's, as residents are, 3D is valued higher. Obviously there is no need for sophisticated imaging modalities if one modality can show that the patient is inoperable (multiple metastases in both liver lobes). With single lesions, or single lobe lesions, the advanced surgical possibilities call for more differentiated imaging and presentation.

The clinicians still are waiting for the most convincing 3D - display. This expectation is to stimulate the further technical development and research.

5. Conclusion

The ideal imaging system displays anatomical objects as a whole. The user then may start peeling off, cutting away, radiographing parts of it and thus may almost realistically simulate the surgical operation. This would mean to have exact information of all objects with highest spatial resolution and to perform in real time. The system of displaying block data does have a potential to achieve this as soon as faster computers are readily available.

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Value of Three-Dimensional CT in Orofacial Surgery

C. Zwicker, M. Langer, F. Astinet, et al

Department of Radiology, UKRV-Charlottenburg, Free University Berlin, WEST GERMANY

Transversal CT slices and 2D reconstructions do not always provide the optimal spatial information of the complex, anatomical structures of the visceral cranium. The 3D CT introduced in recent years has gained increased popularity. The goal of this study was to evaluate the feasibility of the 3D CT in orofacial surgery.

Patients:

Threedimensional image reconstructions were generated in 40 patients with orofacial tumors and 12 patients with fractures (36 males, 16 females, mean age 54 $\pm$ 9 years).

Methods:

Each study was performed with the Somatom Plus, Siemens (continuous rotation of tube and detector). Phantom studies with 2 mm thick and 1 mm overlapping slices were superior to 1 and 5

mm scans in threedimensional rendering. Therefore all scans were made with these parameters and 0,7 s scanning time (60 mas, 120 kv). The time for scanning and threedimensional surface reconstruction lasted from 30-45 minutes.

The 3D surface display offers a spatial representation through a shaded reproduction of the object. Pixels nearer the viewer are imaged brighter, while structures further away are imaged darker. Free selectable cutlines permit the projection of any internal view. Image reconstructions of any projection require a matter of seconds.

Results:

The image quality of the osseous structures was excellent without any artefacts in 24 cases (tab.1, fig.1). The complex destructions or fractures were clearer and easier for the oral surgeon to understand than with transversal slices. A slight reduction of image quality was due to motion or metal artefacts in further 25 patients (fig.2). Sufficient threedimensional images could not be generated for three uncooperative patients.

Table 1:

Image Quality of 3D CT:

very good:	24 patients
good:	25 patients
poor:	3 patients

Discussion:

In concordance with Vannier, Grodd and Totty (1,2,3) our experience has shown, that 3D CT leads to an improvement of the delineation of complex osseous destructions. Additional spatial information can be achieved with this method. But better diagnostic information of the visceral cranium cannot be obtained with the 3D CT, because the image information of transverse CT slices provide the basis for this reconstruction. Discrete bony alterations can only be demonstrated with certainty in transversal CT scans (1).

Thin overlapping slices, short scanning times and reduced mass products provide 3D CT images of optimum quality.

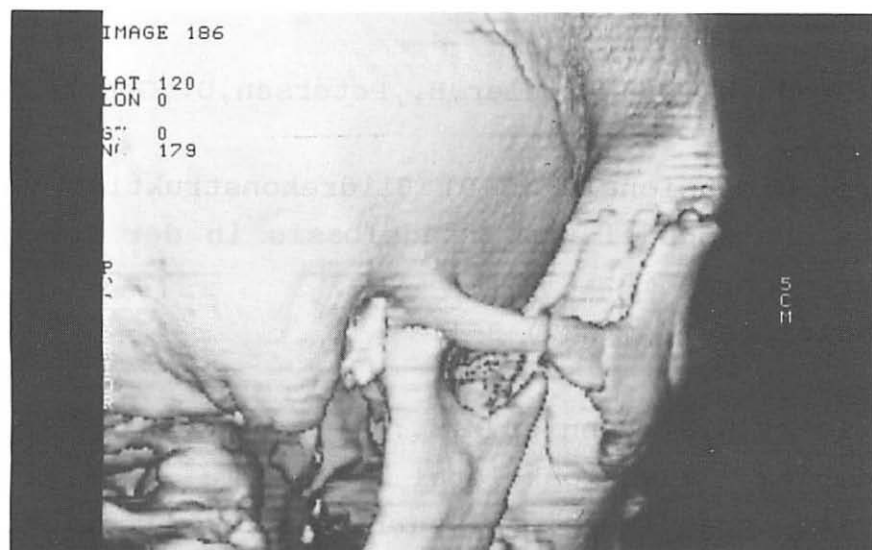


Fig.1:

Cheek-bone and temporal bone fracture.

Very good quality of the reconstructed image.

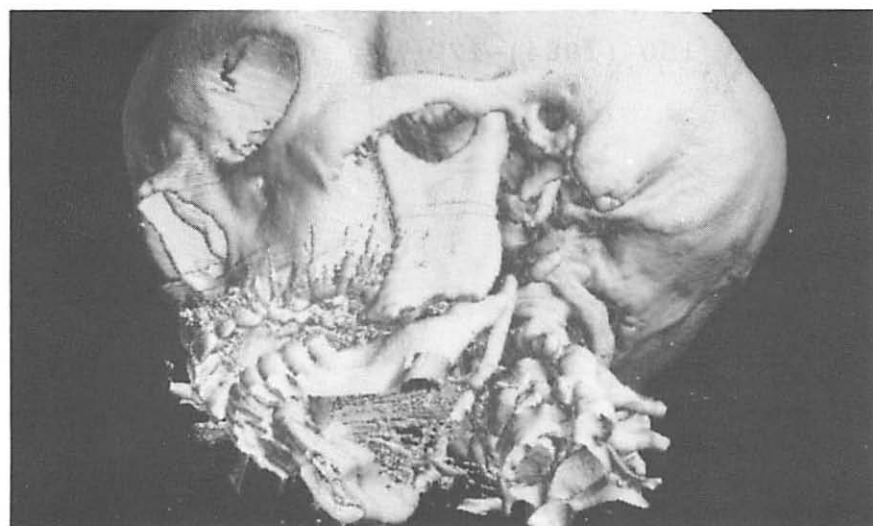


Fig.2:

Fracture of the lower jaw. Slight reduced image quality because of metal artefacts.

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Surgical Planning/Coronary Imaging

Motion Artifact Correction in DSA

Lu Weixue and Zhang Tianxu

Institute of Biomedical Engineering, Zhejiang University,
PEOPLE'S REPUBLIC OF CHINA

1. INTRODUCTION

The need of estimating relative displacements between the images taken at different times and conditions has arisen in a variety of engineering problems such as medical imaging, remote sensing and machine vision. A typical example is digital subtraction angiography. In DSA the vascular information are obtained by subtraction of the mask and the live image. In principle, the difference image contains only the projection of blood vessels. However, visibility of the vessels is hampered by the presence of patient motion. Hence, for any temporal subtraction techniques of DSA, estimating the displacements and reregistrating the original images are necessary.

The conventional methods of displacement estimation are based upon matching the gray level of the two images with different relative displacement, and the position with maximum similarity was selected as the optimum estimation. But in DSA due to the appearance of contrast agent in the live image, matching of gray level does not gave optimal estimation of displacement. Therefore optimal estimation of displacement must consider the gray level change due to contrast agent and other factors.

Some works considered the gray level change caused by contrast agent through using a global gray level compensation. But these works did not consider the time and spatial varying property of the gray level change, therefore the results were unsatisfactory.

2. GRAY LEVEL CHANGE MODEL

In order to consider the local distribution of the vessel system (filled with contrast agent). It is logical that a performance criterion should be some function of gray level change or unknown model parameters which stand for main features of such a change. To characterize the mean spatial-varying features of the vascular system f_I , We divide the image plane into $(J_1+1)(K_1+1)$ subregions $\{b_{j_1 k_1}\}$. For each subregion search of optimum for some criterion R not only in two-dimensional space $(\Delta x, \Delta y)$, but also the gray level change, i.e. searching is in a space of higher order $(\Delta x, \Delta y, f_{I0})$, where f_{I0} is a model parameter reflecting gray level change.

Thus let f_I be the vascular system to be detected, then it can be approximated by f_{I1} :

$$f_{I1}(x, y, t) = \sum_{j_1=0}^{J_1} \sum_{k_1=0}^{K_1} f_{I0}(j_1, k_1, t) r_1 \quad (1)$$

where r_I is a two-dimensional function defined over $\{b_{j_1 k_1}\}$, f_{I1} is an estimation of f_I .

In the simplest case r_I is a zero order function as:

$$r_{I0}(x, y) = \begin{cases} 1 & \text{if } |x| \leq h_x / 2, |y| \leq h_y / 2, \\ 0 & \text{elsewhere} \end{cases} \quad (2)$$

where the size of $b_{j_1 k_1}$ is equal to $h_x h_y$.

In the case vascular system f_I is approximated by $(J_1+1)(K_1+1)$ number of $f_{I0}(j_1, k_1)$ is the gray level change of subregion (j_1, k_1) . f_{I1} can be considered as a low spatial frequency approximation of f_I .

3. ESTIMATION PERFORMANCE CRITERION

The performance criterion used in our method is directly dependent upon the difference of live image f_c and mask image f_m , so referred to as the minimum artifact

criterion.

Considering the correction of gray level change, then error term of f_c and f_m can be modified as

$$e_{jk}(\Delta x, \Delta y, f_{i1}) = f_c(x, y) - f_m(x + \Delta x, y + \Delta y) - f_{i1}(j, k) \quad (3)$$

Use some kind of error function of e_{jk} ,

$$\varepsilon_{jk}(\Delta x, \Delta y, f_{i1}) = \varepsilon(e_{jk}(\Delta x, \Delta y, f_{i1})) \quad (4)$$

then

$$R(\Delta x, \Delta y, f_{i1}(j, k)) = \sum_j \sum_k \varepsilon_{jk}(\varepsilon_{jk}(\Delta x, \Delta y, f_{i1}(j, k))) \quad (5)$$

The error functions commonly used such as $|e_{jk}|$, $(e_{jk})^2$ have some drawback: terms of larger errors have more strong influence on criterion R than other smaller error terms. It would results false estimate of matching as strong interference appears, which is just the case of contrast agent in the vessel system. One of the error functions we used is as follow:

$$\varepsilon_{jk}(\Delta x, \Delta y, f_{i1}) = \frac{A_1}{A_2 + |e_{jk}(\Delta x, \Delta y, f_{i1})|} \quad (6)$$

which makes each term of R have more equal effect on R .

4. PYRAMID APPROACH

Increasing the order of searching space inevitably increases the time needed to estimate the optimal solution, and will made the method unpractical.

To solve this problem, we use an algorithm based on Gaussian pyramid image data. The search procedure proceeds from the top to the bottom of the pyramids. The information obtained at the lower resolution level are used to guide and control the starting search conditions of vector z at the next higher resolution level of the pyramids. The flow chart of the algorithm is shown in Fig. 1. Where (x_0, y_0) denotes the coordinates of the

window, used as the reference template, in f_m (or f_c); (u_0, v_0) is the central coordinates of search area in f_c (or f_m); $(\hat{u}, \hat{v})$ is the estimated correspondence point of (x_0, y_0) ; $(\Delta\hat{x}, \Delta\hat{y}) = (\hat{u}, \hat{v}) - (x_0, y_0)$; x_r, y_r is the space search range; I_r is the gray level search range; I_0 is the initial value of f_{I0} .

5. EXPERIMENTS AND RESULTS

The algorithms were tested on several pairs of X-ray images.

Original information on X-ray films were converted into 512^2 digital matrix denoted f^0 , from which a Gaussian pyramid image sequence: f^1, f^2, f^3, f^4, f^5 was generated, with the sizes: $256^2, 128^2, 64^2, 32^2, 16^2$, respectively.

The matching computation were carried out only on f^5-f^1 .

The size of image windows used in matching be M_L^2 , $L=1, 2, 3, 4, 5$, then we took $M_1^2=64^2, M_2^2=64^2, M_3^2=32^2, M_4^2=16^2, M_5^2=8^2$.

Started from f^5 , 16×16 pixels, 8×8 window, 4 subregions. Estimated gray level change values of the four subregions are:

1	2
7	5

The difference image at level 5 is:

2	0	0	1	2	2	3	3
2	1	1	1	1	0	2	2
3	0	0	0	0	1	2	1
6	2	2	0	1	2	6	5
7	7	7	5	4	3	7	7
5	3	8	7	4	2	5	5
6	2	8	10	8	5	7	7
9	1	4	9	11	14	15	20

The average gray values of the four subregions of the difference image at level 5 is:

1.3	2.0
6.0	7.5

Compare with the result of gray level change estimation, the accuracy is satisfactory.

According to the R at different matching position, the estimated displacement at level 5 is

$$\Delta\hat{x}=3, \Delta\hat{y}=3$$

We use quadratic 2-D interpolation to modify the estimated displacement to an accuracy of 1/10 spatial resolution of the image and found the modified value at level 5 is

$$\Delta x'=-0.1, \Delta y'=-0.5$$

These values are used to control the second iteration (level 4). The process of iteration is repeated until we find the displacement estimation at level 1.

6. CONCLUSION

(1) Estimation of local gray level change by divided the image into subregions is effective to treat the influence of contrast agent in the vessel system.

(2) Pyramid approach of multilevel estimation can accelerate the searching procedure considerably.

(3) A hyperbola error function is better than $|e|$ or e^2 function in this case.

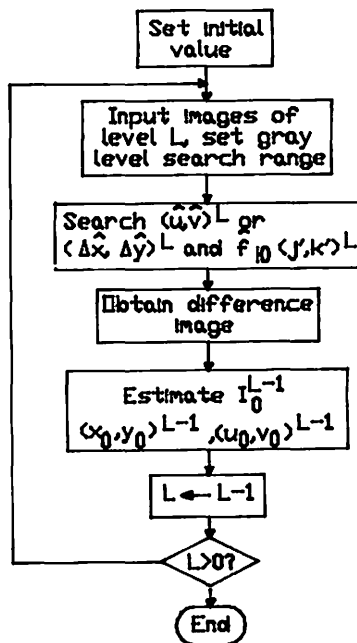


Fig. 1. Flow Chart of Pyramid Approach.

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Toward Reconstructing the Cross Sections of Coronary Arteries From Biplane Angiograms

Luong Van Tran and Jack Sklansky

Department of Electrical and Computer Engineering,
University of California, Irvine, Orange, CA

Robert C. Bahn

Department of Laboratory Medicine and Pathology,
Mayo Clinic, Rochester, MN

ABSTRACT

We describe an algorithm that reconstructs the cross sections of the lumens of coronary arteries from two mutually orthogonal x-ray projections. In other techniques of reconstructing these cross sections from biplane images it is assumed that the cross sections are elliptical. Although this assumption is valid in healthy portions of the artery, stenotic portions can have crescent or star shapes as well as elliptical. Our algorithm accommodates the possibility of such shapes. Our algorithm represents each biplane projection of a transverse slice of the arterial lumen as a binary-valued image. The single-coordinate moments of these two binary-valued images are matched to those of an initial binary-valued image of the slice. Since the cross-coordinate moments of the slice cannot be matched to those of the biplane projections, we represent the slice as a sum of weighted Legendre polynomials. The weights are estimated by an iterative procedure involving singular value decomposition. Preliminary tests of our algorithm on synthetic data as well as on biplane images of a segment of a barium enhanced *in vitro* heart are reported.

I. INTRODUCTION

Knowledge of the shapes and sizes of the lumens of coronary arteries enables the estimation of several important clinical parameters [1]. In several techniques for 3-D reconstruction of coronary arteries it is assumed that the cross sectional shapes of the coronary arteries are elliptic [2],[3],[4],[5]. Although this assumption is valid when the arteries are healthy, it may not be so for stenoses. Stenoses may have crescent or star-like shapes as well as elliptic [12]. In this paper, we suggest a means of reconstructing such a shape from two orthogonal x-ray projections of the arteries. We describe the underlying mathematical theory and report

the results of preliminary tests on synthetic data, and a segment of an *in vitro* heart.

As in earlier work on this subject we view the three-dimensional reconstruction of a coronary artery as the reconstruction of a stack of slices. In each slice, the cross section of the vessel is given by the density profile along each horizontal scan line. Assuming that the contrast medium within the vessel is distributed homogeneously, we represent each cross section as a binary-valued image, where pixels have the value of 1 if they belong to the vessel and 0 otherwise. Thus the problem of finding the cross-sectional area of the vessel in each scan line from the two orthogonal projections is transformed into the problem of reconstructing a binary-valued image from its row and column sums. We represent such an image by a matrix whose elements are restricted to 0's and 1's. We refer to this as a binary matrix.

The problem of reconstructing a binary matrix from its row and column sums is indeterminate, i.e there may be no, one or several solutions. Consider a binary matrix I with U rows and V columns. Let $R(i)$ represent the sum of row i , and let $C(j)$ represent the sum of column j . Then we have:

$$R(i) = \sum_j I(i, j) \text{ for } i = 1, \dots, U$$

and

$$C(j) = \sum_i I(i, j) \text{ for } j = 1, \dots, V$$

When we try to solve for the value of each pixel within the matrix I , we usually encounter more than one solution since we have U times V variables and only $U+V$ equations.

II. PREVIOUS WORK

In [6], Chang and Chow described a means of reconstructing a binary image from two orthogonal projections, based on the assumption that the object is convex symmetric. Later in [7], Chang and Wang showed that, for a convex symmetric binary object, if one contour position is known, the shape can be uniquely reconstructed from two orthogonal projections.

Onnasch *et al.* [8] described a technique for reconstructing the left and right coronary ventricles from biplane angiograms, using the reconstruction of an adjacent slice and of the same slice in an other phase of the cardiac cycle. The values of the pixels within the binary matrix were determined from an array of probabilities. Slump and Gerbrands [9]

described a method of finding a binary matrix that satisfy the two projections with maximum resemblance to adjacent slices (temporally or spatially) based on a cost function. This method is called the *minimum cost capacitated network flow* algorithm.

All of the above techniques were devised for reconstructing coronary ventricles. Reiber *et al.*[1] adapted Onnasch's and Slump's algorithms into reconstructing coronary artery cross sections. Good results were obtained. A problem with this approach is that sometimes the a priori information does not exist, as in the case of the first slice. This can be circumvented by having the user select the slice where he/she is quite sure that the shape is elliptic. However, as stated in [1], in a stenotic segment the two neighboring slices of a particular slice might be very different. Our approach, described below, overcomes this difficulty.

III. MATHEMATICS OF RECONSTRUCTION

In this section, we present the mathematical theory supporting our approach to reconstructing a binary matrix from its projections. If the domain of $F(x, y)$ is continuous the two-dimensional moment f_{pq} is defined as

$$f_{pq} = \int \int x^p y^q F(x, y) dx dy \quad (1)$$

If the domain of $F(x, y)$ is discrete

$$f_{pq} = \sum_x \sum_y x^p y^q F(x, y) \quad (2)$$

If the function $F(x, y)$ is piecewise continuous, bounded and has nonzero values only within a finite part of the xy plane, then moments of all orders exist and the following uniqueness theorem applies [13].

Uniqueness theorem: The set of all order moments f_{pq}

is uniquely determined by $F(x, y)$, and *vice versa*.

Thus if the domain of $F(x, y)$ is continuous, its reconstruction may be obtained from an infinite number of moments. In reconstructing a binary matrix from its row and column sums we are constrained to do so without any of the cross-coordinate moments. Below we summarize our approach to solving this problem, based on the orthogonal moment method described by Teague [10].

If $F(x, y)$ is assumed to be piecewise continuous over the basic interval, then it can be expressed as

$$F(x, y) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} L_{mn} P_m(x) P_n(y) \quad (3)$$

where $P_m(x)$ is the Legendre polynomial with normalization

$$\int_{-1}^{+1} dx P_m(x) P_m'(x) = \frac{2}{2m+1} \delta_{mm'} \quad (4)$$

and the orthogonal moments L_{mn} , defined by

$$L_{mn} = \frac{(2m+1)(2n+1)}{4} \int \int F(x, y) P_m(x) P_n(y) \quad (5)$$

are related to the moments f_{mn} by

$$L_{mn} = \frac{(2m+1)(2n+1)}{4} \sum_{j=0}^m \sum_{k=0}^n C_{mj} C_{nk} f_{jk} \quad (6)$$

Equation (3) enables the reconstruction of the binary matrix. This equation is sufficient if we have all the moments f_{mn} up to the order N_{max} . Below we describe how f_{mn} may be estimated from the two projections. Let $F(x, y)$ be the binary matrix that is to be reconstructed. Let $A(x, y)$ and $B(x, y)$ represent the column sum and row sum projections of $F(x, y)$ expressed in the form of two binary matrices.

Let f_{pq} , a_{pq} and b_{pq} be the moments of order p, q of $F(x, y)$, $A(x, y)$ and $B(x, y)$ respectively. They are defined as follows

$$f_{pq} = \sum_x \sum_y x^p y^q F(x, y)$$

$$a_{pq} = \sum_x \sum_y x^p y^q A(x, y)$$

and

$$b_{pq} = \sum_x \sum_y x^p y^q B(x, y) \quad (7)$$

It can be shown that $f_{0q} = b_{0q}$ and $f_{p0} = a_{p0}$ for any p and q . However, all cross-coordinate moments, i.e. all f_{pq} where both p and q are greater than zero, are missing. These moments must be estimated. Let the

dimensions of the three matrices $F(x, y)$, $A(x, y)$ and $B(x, y)$ be U rows by V columns. Let

$$S_i = \sum_y y^q A(x_i, y)$$

$$Z_i = \sum_y y^q B(x_i, y)$$

$$C_i = \sum_y y^q F(x_i, y) \quad i = 1, \dots, U \quad (8)$$

To estimate C_i , we define a_i and b_i such that

$$C_i + a_i = S_i \quad i = 1, \dots, V \quad (9a)$$

$$C_i + b_i = Z_i \quad i = 1, \dots, V \quad (9b)$$

In addition to the $2V$ equations given in (9), we have an additional equation, namely:

$$\sum_i C_i = f_{0q} = b_{0q} \quad \text{for any } q \quad (10)$$

Equations (9) and (10) give us $2V + 1$ equations for $3V$ variables (C_i, a_i, b_i) .

Note that the number of equations is less than the number of variables. To solve this we use singular value decomposition (SVD) described in [11]. This leads to an iterative procedure that is the core of our shape estimation algorithm.

The value of N_{max} is determined by the degree of irregularity in the shape of the cross section we want to reconstruct. For typical shapes of stenotic coronary arteries the value of $N_{max}=10$ seems to be adequate.

IV. ALGORITHM

Our algorithm for reconstructing a binary image from its row and column sums is as follows:

Step 1. Pick an initial $Q < N_{max}$ (experimentally $N_{max} - Q$ is about 3 to 5).

Step 2. Rearrange matrix $B(x, y)$ by interchanging its columns such that $|S_i - Z_i|$ is minimum in each column i .

Step 3. Set up the $2V+1$ equations as described in (9) and (10)

Step 4. Solve for the missing moments up to order Q .

Step 5. Use Equations (3) and (6) to obtain the resulting image $R(x, y)$.

Step 6. Calculate the error e of $R(x, y)$. This error is defined as $e = |a_{p0} - r_{p0}| + |b_{0q} - r_{0q}|$ for $p, q = 0$ to Q where r_{0q} and r_{p0} are the moments of $R(x, y)$.

Step 7. From R generate two new profile matrices $A'(x, y)$ and $B'(x, y)$ such that the column sums of $A'(x, y)$ are equal to the ones of $A(x, y)$ and the row sums of $B'(x, y)$ are equal to the ones of $B(x, y)$.

Step 8. Replace $A(x, y)$ and $B(x, y)$ by the new $A'(x, y)$ and $B'(x, y)$. Iterate from Step 3 until the error cannot be minimized further.

Step 9. Increment Q . If Q is greater than N_{max} , go to step 10. Otherwise, go back to step 3.

Step 10. Optimize the resulting image against the original row and column sums by the following procedure:

- (i) From $R(x, y)$ create the two profile matrices A' and B' as in Step 7.
- (ii) Calculate the row sum errors of A' and column sum errors of B' . If these errors are equal to zero, exit.
- (iii) Merge A' and B' (by ANDing each pixel of A' with the corresponding pixel of B') to create a new matrix R' .
- (iv) Replace R by R' and iterate from (i) until the errors cannot be made smaller.

V. EXPERIMENTS

V.1 Synthetic data The reconstruction algorithm was tested on synthetic binary images representing commonly encountered shapes of coronary arteries, both healthy and stenotic: elliptic, crescent and star-like. The results are given in Figure 1. In each figure, (a) is the image to be reconstructed, and (b) is the reconstruction. Note that for the ellipse,

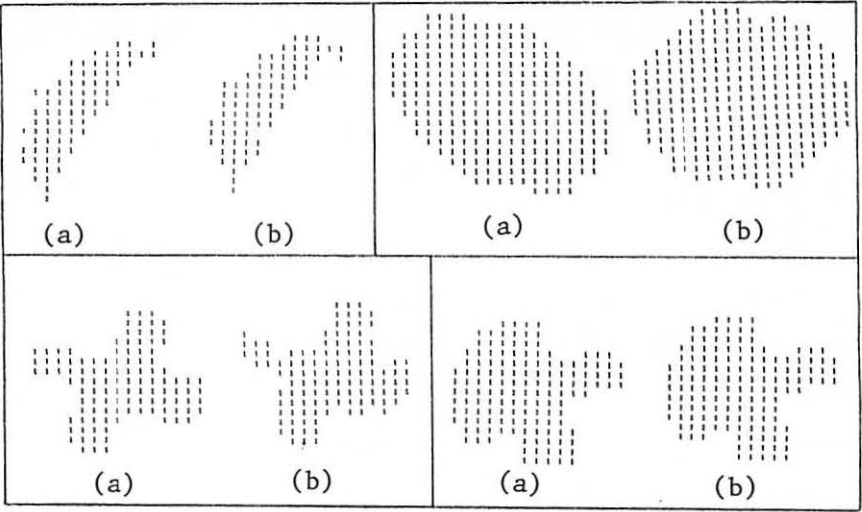


Figure 1: Synthetic data

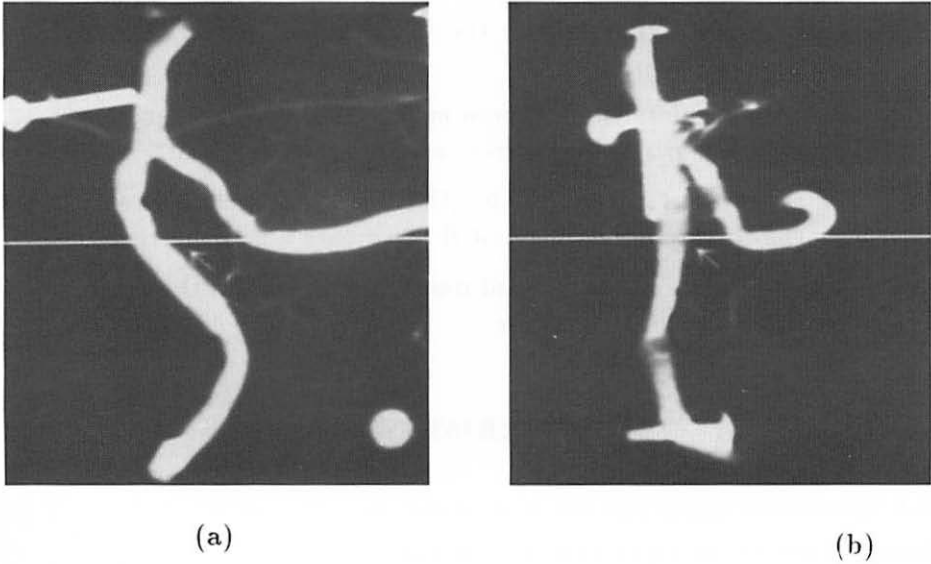


Figure 2: Biplane images



Figure 3: Reconstructed cross section

the algorithm gives a reconstruction which is elliptical but the eccentricity and the orientation of the minor and major axes are wrong. This defect can be avoided if we are given additional information such as the 3-D orientation of the artery.

V.2 Segment of *IN VITRO* heart

For our experiments on a segment of an *in vitro* heart we obtained angiograms at the Mayo Clinic in Rochester, Minnesota using General Electric Fluoricon 300 biplane AP and LAT x-ray machine, with tungsten target, having a focal spot size of 1.0 mm and a Bucky grid. The set-ups for the two views differ. For the AP view, the x-ray source provides 100 ma, 60 kvp, with an exposure time of 0.003 sec. The distance from the focal spot to the object is 57 cm and the distance from the object to film is 23 cm. For the LAT view, the power is 50 ma, 70 kvp, and the exposure time is 0.005 sec. The distance from the focal spot to object is 57 cm and the distance from the object to film is 23 cm. We used KODAK T-MAT L films, 24x30 cm. The film was digitized on a MASCOMP 5700 computer using a Grinnell digitizing package with an RCA video camera with a 25mm lens. Figure 2 shows a biplane pair of a portion of an *in vitro* heart whose arteries are filled with barium. The three pins serve as fiducial points.

Figure 3 shows the reconstructed cross section, at the stenosis marked by the white line in Figure 2. The asymmetric shape of the reconstructed cross section suggests the presence of arteriosclerotic plaque in the lower right quadrant of the figure. This and other regions of the coronary arteries are in the process of being examined microscopically.

VI. SUMMARY AND CONCLUSION

We have presented a method of estimating the cross-sectional shapes of coronary arteries from two simultaneous orthogonal projections. This method is based on a new technique for reconstructing a binary matrix from its row and column sums. Preliminary tests of this technique on synthetic data and on biplane images of a segment of an *in vitro* heart yield encouraging results.

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Automated Analysis of Heart Size in Digital Chest Images: Effect of Heart Size Parameters on Detection of Cardiomegaly

Steven M. Montner, Nobuyuki Nakamori, Kunio Doi, et al

Kurt Rossmann Laboratories for Radiologic Image Research,
Department of Radiology, University of Chicago, Chicago, IL

Cardiac size is an important and useful diagnostic parameter in chest radiographs. However, there is a large variation in the subjective judgement of cardiac enlargement, and a confident distinction between normal and abnormal can be difficult. In order to reduce this subjective element, we are developing a semi-automated system for quantitative analysis of heart size in digital radiographs. Boundary points along the mediastinum are determined by detecting the points from an analysis of edge gradients in two orthogonal directions. Heart boundary points are selected, and fitted to a "shift-variant" cosine function, to predict the entire cardiac outline. We also detect edges of the rib cage and diaphragms, and several parameters related to the heart and thorax are determined.

Four hundred chest radiographs were reviewed by three radiologists specialized in chest radiology and were classified by consensus into two groups: those with and those without cardiomegaly. These radiographs were used to construct a preliminary database for determination of cardiomegaly. Numerous parameters related to heart size were obtained from the semi-automated analysis of these radiographs, and the utility of each parameter for the detection of cardiomegaly was evaluated by means of ROC analysis. We examine whether the accuracy would be improved by applying multivariate analysis to a pair of parameters. From the analyses of the individual parameters, the cardiothoracic ratio was found to be the single most effective measure for detecting cardiomegaly in chest radiographs. However, multivariate analysis provided results superior to those obtained with an individual parameter.

An index of the likelihood of cardiomegaly was derived from the parameters of cardiothoracic ratio and cardiac area. An observer study was performed in which 12 radiologists were presented a random sample of 90 chest radiographs with cardiomegaly and 90 without cardiomegaly. Between two sessions, each observer was presented each radiograph with and without the computer generated index of cardiomegaly. ROC analyses of these individual radiologists using their own subjective criteria, and also as modified by the results of the automated analysis of heart size, are compared with the results of the automated analysis alone.

Determining Cortical Volumes in Hand Radiographs

Tod S. Levitt, Marcus W. Hedgcock, Jr., Vera M. Shadle, et al

Center for Computed Imaging, San Francisco VA Medical Center,
San Francisco, CA and Department of Radiology, University of
California, San Francisco, CA

John W. Dye and Scott E. Johnston

Advanced Decision Systems, Mountain View, CA

ABSTRACT

The total cortical volume is potentially a valuable index of the degree of bone loss in osteoporosis. Cortical width was used in prior years as an index, however it was poorly reproducible and represented only a very small fraction of the total body bone mass. The cortical volume of the hand represents a much larger percentage of total body bone mass, and is contained in a single radiograph.

Digital radiographs make it possible to use a computer to assist in computing accurate cortical volumes. The technique is to first outline, i.e. contour or segment, the external phalanx and metacarpal boundaries, so that counting the pixels enclosed in the boundaries gives the total projected hand bone volume, (the cortex plus the medullary space). Outlining the internal cortical boundaries and counting enclosed pixels gives us the volume of the projected medullary space. The difference of these values is the estimated cortical volume.

In order to make the use of cortical volume a cost effective procedure, it is necessary to automate the segmentation and volume computation of the hand bones and cortical boundaries. We have developed an interactive environment for extracting intercortical boundaries, and are in the process of developing automated algorithms based on current computer vision and artificial intelligence techniques.

CORTICAL VOLUME MEASUREMENT

Degeneration of cortical bone cell walls is a common symptom of osteoporosis and arthritis. Measurements of this degeneration are useful for diagnosis, tracking, and treatment of these diseases. Measures include quantitative methods for determining bone density and demineralization [Resnick et.al.-81], intercortical width [Forrester et.al.-73], and periarticular demineralization [Thijn-86]. Cortical volume has also been used [Lusted et.al.-77], but is usually replaced by measures of intercortical width due to the time required to manually obtain the estimated volume. Besides being labor intensive, manual measurements suffer from inter- and intra-operator variation. Levitt and Hedgcock have proposed the application of computer vision techniques to automate these measurements in order to provide them more

accurately, repeatably, and cost-effectively to diagnosing physicians [Levitt et.al.-89b]. We therefore have two goals: to determine the efficacy of computer measurements, and to automate their calculation. In this paper we discuss recent work toward these goals in the measurement of cortical volume in hand radiographs.

The cortical volume is defined to be the volume occupied by the bone cortex of the phalanges and metacarpals of the hand. Of more interest is the measurement of the ratio of the cortical volume to total bone volume, as this measure is inherently less sensitive to variations in patient positioning, scanner parameters and geometry. The gold standard for this measurement is obtained from the count of voxels in a CT image of the hand that is optimized to distinguish bone cortex. One of our goals is to determine the accuracy of the approximation of this ratio from cortical volume measured in a computed or digitized radiograph. To this end, the phalanges and cortical boundaries must be interactively segmented (i.e. contoured) and measured. Figure 1 shows results of this process on a Sun 3/160 using software developed in Commonlisp and CLOS at Advanced Decision Systems. Figure 1(a) is the original on-line radiograph from the Philips Computed Radiography system. Figure 1(b) shows the results of interactive contouring of the cortical volume. In this black and white reproduction, the boundaries are more evident on the distal phalanges.

The interactive extraction is a time consuming process, requiring approximately an hour to segment the phalanges in a single hand. Furthermore, the results are errorful and difficult to repeat, as there is no quantitative basis on which to chose a best boundary.



Figure 1(a): On-line Computed Radiograph



Figure 1(b): Interactive Cortical Boundary Extraction

In a radiograph, of course, the entire bone cortex is projected into two dimensions. Radiograph pixels are (essentially) sums of voxels along the lines of projection. As such, some pixels include energy both from voxels of the cortex and the medullary space; thus, there is no "correct" classification of these pixels. However, the pixel segmentation is not the end result; it is the volume estimate we are interested in. The correct volume can be obtained by counting the fraction of a pixel that is proportional to the percentage of cortex voxels that were projected into the pixel. Although sub-pixel accuracy in segmentation is the ultimate goal, it is useful to do segmentation accurate to a pixel in order to compare against human performance in interactive segmentation, and to evaluate the potential gain in accuracy from the more computation intensive sub-pixel accuracy algorithms.

AUTOMATION APPROACH

The key issue is to develop computer vision algorithms that allow a system to automatically find the boundaries and axes of phalanges and the cortical boundary of the medullary space. The process of finding the phalanges and related tissue boundaries is called segmentation. If segmentation can be automated, then the cortical width and volume can be obtained quantitatively by counting pixels and multiplying the result by a conversion factor to obtain measurements in square centimeters. With the Philips Computed Radiography scanner, each image is recorded with a border grid marked in centimeter tic marks, so the conversion factor

can also be determined automatically without knowledge of the relative geometry of the scanner and patient. With the Dupont Laser Film Digitizer, the scanner position relative to the hand must be known or inferred from a standard object placed in the field of view of the radiograph.

In the model-based evidential reasoning or evidential accrual approach to automated segmentation, we regard feature values, observed image structures, shape measures, etc. as being evidence supporting or denying hypotheses of what anatomy is imaged and how it is oriented relative to the imaging sensor [Binford et.al.-89]. Additional hypotheses of possible abnormalities (e.g. fractures, calcification, tumors, carcinomas, etc.) can also be reasoned about using this approach if appropriate models can be formulated. The components of this approach are models of anatomy, a well-defined space of hypotheses and evidence, and a mathematically sound methodology for accruing evidence in support or denial of the hypotheses.

We take the point of view that our hypotheses are instances of matching the imagery data to the anatomy that we have developed models for. Thus, the development and construction of accurate computer representations of 2D and/or 3D anatomical models that are valid over human populations is a fundamental step to realizing this approach. For hands, some population statistics are available in the literature for normal distributions of lengths, widths and ratios of phalanges and metacarpals [Poznanski-74], [Meschan-75]. These permit us to begin modeling phalanges as cylinders with joints and joint spaces modeling appropriate connectivity between phalanges. We are enhancing these models to more accurately represent phalanges as we gather statistics on the variance of widths along phalanges by making measurements in radiographs. When a geometric and statistical model of the hand is partially matched to features extracted from a radiograph, we can use mathematical projection of the model, anchored by the feature matches, to predict where other, finer, anatomic features lie in the image. Then more refined image processing operators can be brought to bear to find evidence for the exact location of the anatomical features.

Results of segmentation of phalanges have been shown by Levitt and Hedgcock [Levitt et.al.,-89a], [Levitt et.al.-90]. A typical example of phalanges segmentation is shown in figure 2. In the following we expand on the the image processing operators used to extract evidence of the presence of the cortical boundary between the bone cortex and the medullary space.

CORTICAL BOUNDARY EXTRACTION

The cortical boundary is more obvious away from the ends of the phalanges where the contrast between the cortex and the medullary space is more pronounced. However, even in the mid-phalanx, the boundary of the cortex can be faint because of the radiographic projection. In order to apply model-based techniques to finding the cortical boundary, we make the assumptions that the cortex is of uniform (although unknown) thickness, t , and uniform density at any one transaxial cross-section, although it varies between cross-sections, and that the transaxial cross-sectional shape of the phalanx is approximated by a hemi-ellipse as pictured in

figure 3. A and B represent the radiographic image intensities projected through adjacent neighborhoods of width w . Determining the cortical boundary from the radiograph is equivalent to the problem of estimating t for each transaxial cross-section.

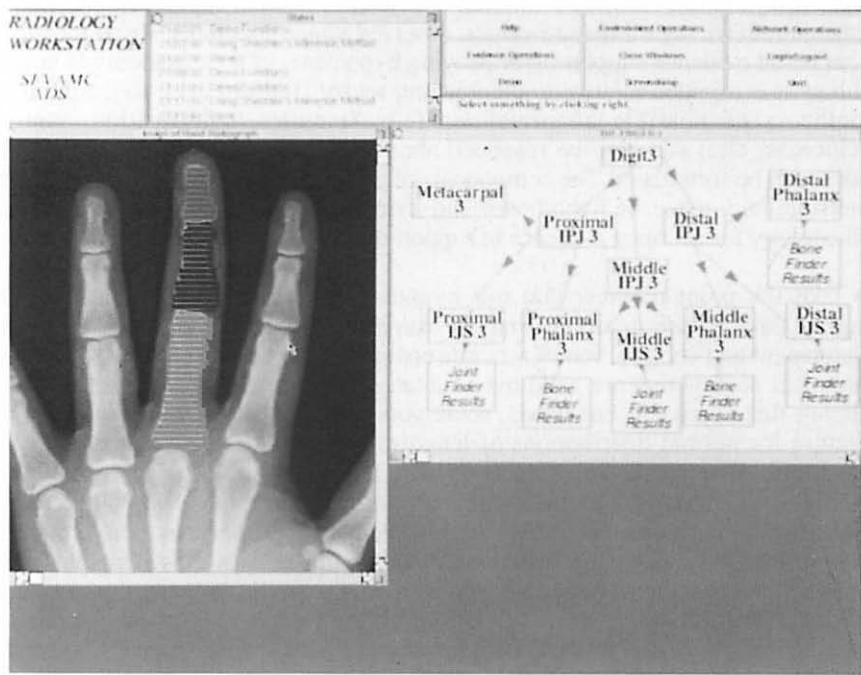


Figure 2: Automated Phalanx Segmentation

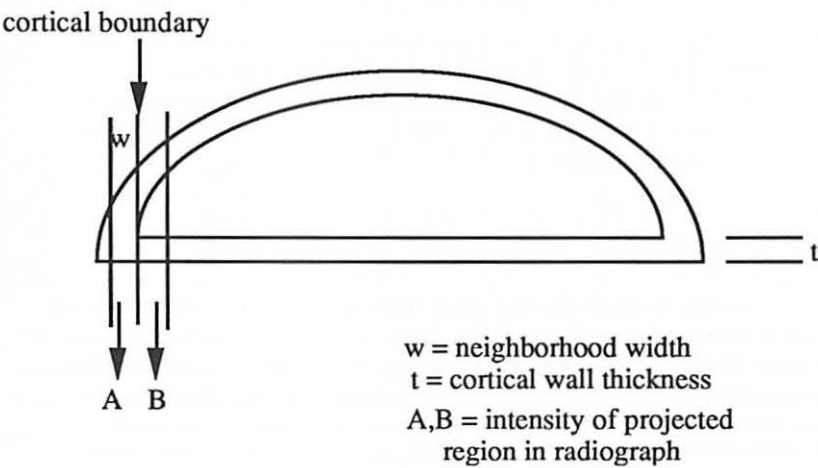


Figure 3: Phalanx Cross-Sectional Geometry

In this figure, A is the projection through the cortex only, while B is a projection of both cortex and medullary space. The expected ratio in radiographic image intensity at these locations is the basis for detection of the cortical boundary. We chose the neighborhood width, w , such that w is less than or equal to t , because it is the gradient across the cortical boundary that we are interested in. Under the above assumptions, if the interval $[s, s+w]$ corresponds to the location of A and the interval $[s+w, s+2w]$ represents the location of B, then the ratio of radiograph intensities, A/B , is given by

$$r(s, t, w, a, b) = \frac{\int_{s+w}^{s+2w} \sqrt{b^2 \left(1 - \frac{x^2}{a^2}\right)} dx}{\int_s^{s+w} \left[\sqrt{b^2 \left(1 - \frac{x^2}{a^2}\right)} - \sqrt{(b-t)^2 \left(1 - \frac{x^2}{(a-t)^2}\right)} + tw \right] dx}$$

where a is the width of the phalanx and b is the phalanx depth, t is the cortical thickness and w is the half-width of the neighborhood over which the ratio is being calculated.

Notice that we choose s and w , and a and b are either taken from population estimates for phalanx measurements, or a can be read from the radiograph and b can be estimated (e.g., if a hemispherical cross-section is assumed, then $a=b$). With this in mind, t becomes the only unknown parameter.

In our model-driven approach to tissue segmentation, we hypothesize and test different values of t by comparing the prediction (above) against the ratios obtained in the radiograph. Note that we can find the transaxial cross-section automatically, because we can already segment the phalanges themselves and locate the longitudinal axis [Levitt et al.-89(a),90]. We then use this as evidence in the probabilistic accrual for automatic segmentation. Figure 4 shows the result of localized cortical boundary extraction in a radiograph of an arthritic hand.

SUMMARY AND FURTHER WORK

Cortical volume is a useful indicator in diagnosis and treatment of arthritis and osteoporosis. The volume can be approximated by measurements in digital hand radiographs. We have developed a computer environment to perform these measures. However, this is a labor intensive, errorful process that renders the measure insufficiently cost-effective to be used in clinical applications.

We have developed an approach to automatic segmentation of tissues of the hand that utilizes model-based evidential reasoning to segment demineralized and normal hand anatomy in PA views in computed (i.e. digital) radiographs. This allows the system to automatically obtain measures of cortical volume and intercoritcal width.

A key step in automation is the development of image processing operators that can reliably segment the cortical boundary. Initial results of cortical boundary extraction were demonstrated. We are continuing to automate the extraction of cortical boundaries. In addition, we are beginning clinical studies to quantify the accuracy of the measures in radiographs against the CT measurement of cortical volume.

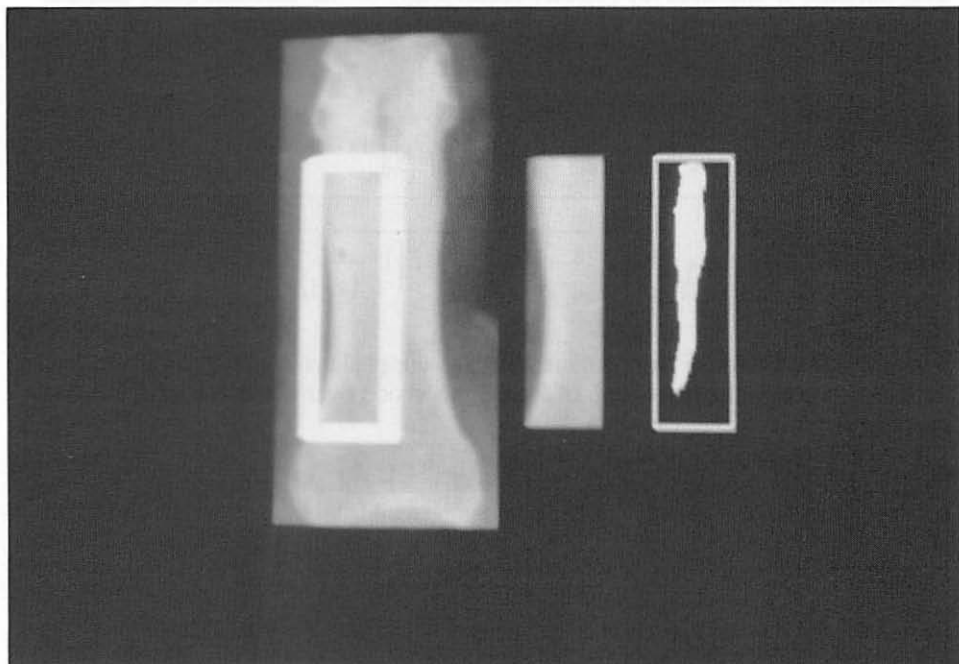


Figure 4: Localized Cortical Boundary Extraction

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An Experimental Environment for True 3D Surgical Planning by Simulation—Methods & First Experimental Results

U. Tronnier, F. Hasenbrink and A. Wittich

TU-Berlin, Fachgebiet Computer Graphics, Berlin, WEST GERMANY

Abstract

We have developed an experimental environment for multi-modal 3D reconstructions such as CT, MR, and PET which aids 3D dissection. Due to the model-properties of the used XCE model we are able to integrate the results from 3D therapy planning procedures such as radiation therapy planning, stereotactic biopsy planning and viscerocranial investigations into the model and, thereby, the 3D reconstructions.

Introduction

Over the last decade 3D reconstruction and/or visualization algorithms for radiological slice data have been developed. They result in some cases in a high degree of realism /Herman86, Höhne87, Toennies87, Drebin88, Levoy88/. Some authors do not concentrate on visualization but on therapy planning. While the early systems were only 2D the more advanced developments use common CG/CAD techniques as a planning tool /Aldinger89, Becker89, Schmitz89/. Several attempts were made to do true 3D therapy simulation with more complex functions for the therapeutical planning procedures /Goitain83a, Goitain83b, Toennies89, Tronnier89, Fujioka89/. This could be achieved by development of tools and handling functions as they were used in the operating theater and/or the therapy equipment. The presented system, described here from a technical point of view, was specified by interdisciplinary cooperation of surgeons, radiologists and computer scientists.

3D Modelling, Reconstruction and Segmentation

An experimental environment was built in an extendable form which is based on the XCE model /Stiehl87, Tronnier89, Tronnier90/. This model is an extension of the well known cell enumeration model used by several authors /Höhne87, Levoy88, Drebin88, Jackèl87/ in a three fold way: First, the voxels have nonisometric properties: their dimension in z are different from their dimension in x and y . Second, the dimension of every voxel is assumed to be greater than one (and less than three due to memory restrictions). Each dimension represents a different property, e.g. CT

values, MR signals, segmentation information, results of surgical planning procedures and has a distinct information depth. Third, due to the strong need to structure the data a scene graph is associated to the XCE scheme via the segmentation information. Switching between the two is possible either by direct addressing the scene description using the voxels properties or by associative addressing of voxels from the graph side. The graph represents segmentation and user supplied information created during a dissection process as well as information generated by the therapy simulation procedures (figure 1).

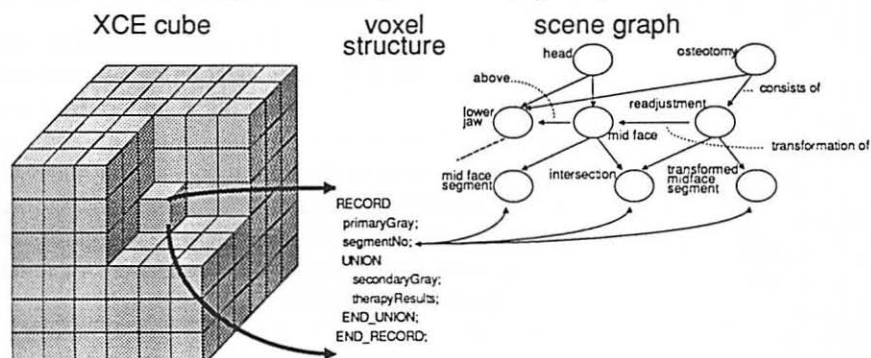


Figure 1: Representation of the XCE model and the connected scene graph

Having the slice data converted in our voxel representation 3D reconstructions may be created directly by multimodal thresholding, VOI, and 3D-cutaway definitions. They can be rendered with transparency for a more comprehensive display of topological relations. However, the main task is not reconstruction but dissection. It is based on these 3D reconstructions (in particular these reconstructions were only 2½D) and appropriate conditions as well as an interactive 3D region growing algorithm. For the whole process, which we call "non invasive preparation", a free configurable volume renderer and a scene graph administrator was implemented. Both were based on the same set of conditions for selecting voxels. They generate 2½D pictures from the 3D scene in 6 minutes in a draft form while segmentation works in near real time on a SUN 4/330 (figure 2). More sophisticated visualizations require 10 times of the computational costs by a radiosity-like algorithm.

3D Therapy Simulation

Based on the graph description, the XCE model and the 2½D pictures therapeutical planning can be done by simulation. Three application fields were evaluated: radiotherapy planning, stereotactic biopsy planning and simulation of maxillo-facial osteotomy. Simulation results were automatically integrated in the scene description by a set of graph theoretical operations. They can be rendered by the same ray casting algorithm as described above by specifying some additional parameters.

In the case of radiotherapy planning simulation leads to calculation of energy distribution. It can be solved by perspective casting "gamma" rays from a virtual energy source into the XCE volume according to the geometrical relations of the therapy equipment (e.g. point of gamma source, collimator shape, patient position). Along the rays dose values were calculated by using voxel specific absorption factors derived from the HU values. In conjunction with ray casting this gives the ability to consider path length and internal anatomic structures. In this way anatomic and simulation data can be rendered in one image based on voxel data (figure 3).

In our opinion the ray casting approach for dose calculation has two advantages: First, the algorithm is very similar to the visualization counterpart and, therefore, may be integrated with it. Second, using numerical integration of the voxel attenuation rather than calculating the gamma ray's decline results in artificial simulation film patterns for the patient's position in the therapy device /Tronnier90/. Since less storage access is needed we hope to reduce calculation time by doing three tasks in one pass. More sophisticated algorithms taking scattering, ionisation and secondary electron emission into account are known /Sack87/ and may substitute our simple dose calculation in a later pilot implementation.

Biopsy planning is the second field of our research. Based on 3D reconstructions of the skull, the brain vessel system and the segmented pathologic regions the surgeon first defines a target point to anchor the biopsy needle and then turns the needle freely around this anchor point until a good choice is found. As shown in figure 4 collisions of the needle-defined "cone of risk" with the vessel system can be detected automatically. In any case the system tests the surgeon's needle way against the properties of the stereotactic frame system, presented in /Rhodes83/, and finally yields the five stereotactic parameters from which the user has to supply only three: the target point and two angles of the needle pathway.

We plan to enhance the biopsy planning aid by introducing a "needle's eye view" function which allows the surgeon to estimate distances between the path of the needle and surrounding vessels. But during needle motion this functionality definitely requires real time volume (scan) conversion of the "cone of risk" and rendering capabilities of the underlying visualization system.

Planning of viscerocranial surgery is an application field with strong 3D needs. Our idea is to supply the surgeon with a "box" of familiar tools and handling functions which he knows from his daily work: drills, curettes, mills and saws as well as handcrafts for bone readjustment and aids for implant design. Using such a set of tools the surgeon may simulate the investigation considering all topological information in 3D.

From our technical point of view we classify eroding, grafting and transformation functions. Eroding tools require the determination of the intersection

of the XCE voxel set and the geometrical shape of the tool's working point and trajectory. Grafting functionality requires either the use of techniques for free form surface design, mirroring operations or, the so called, off block modelling by the above mentioned eroding functions. Again, in either case, the quick volume (scan) conversion algorithms seem to be the problem. This can also be applied to the last group which is specified as the transformation functions. Affine transformations of voxel sets require a significantly higher computational effort than the geometric models. This is mainly true due to the greater set of objects to be transformed. But, moreover, this is an effect of error minimization necessary due to partial volume effects of the nonisometric discrete transformation.

Interaction

Not only the modelling algorithms have to be adapted for use with medical data but also the interaction techniques. One problem seems to be the design of suitable interaction techniques for deriving algorithmic parameters in 3D from 2½D images by 2D interaction. We use a technique with stacked computational effort because we cannot achieve real time while using 3D voxel modelling: The surgeon graphically describes his task based on a 3D reconstruction with geometrical tools (e.g. drill, working point and direction as well as diameter and depth, see figure 5) and the system generates some fast previews and slice reconstructions of the expected results. Using this information the tools application can be initiated. It results in a volatile XCE description. Based on this representation 3D reconstructions of the tool application may be generated. If they seem to be convenient the volatile information could be freed up and included into the scene graph representation.

Other interactive tools than the already mentioned drilling tool were more difficult to implement: Saws may work planar or in a free form fashion (like a pad saw). The latter requires tactile feedback between a 3D cursor and/or interaction device and the user. The user has to sense if his tool is "on" the surface. The program needs not only knowledge about the working point but also the 3D orientation and the user's pressure. This is especially true for tools like curettes and mills which have to calculate something like penetration depth. Figures 6, 7 and 8 show a planar saw and the results of the sawing and milling operation.

Interaction techniques for transformations were based on the calculation of the segment's principal axis. It results in a local coordinate system which is integrated in the 3D reconstruction in order to give the user an orientational help facility. Based on overlays like the one showed in figure 9 and a 3D interaction device for inputting angles, the local system may be repositioned in place and orientation. Herewith the display of the transformed unit vectors of the local system gives the user an impression of the resulting segment transformation because real time segment transformation and display are not achievable at the current state using voxel models. In this way figure 10 of an readjustment osteotomy was created.

Creating interaction techniques for free form bone grafts seems to be the most difficult task. Common CAD systems would accomplish this but we think they are not adequate for users in the field of medicine. Our aim is to support them with a maximum of information derivable from 2½D pictures. This is done by a fast calculation of depth reconstructions along the free form grid and the grid itself. This gives the user a hint of the 3D extension, shape and bone fitting of his implant. The main prerequisites are the real time facilities of rendering during interaction and the suitable 3D interaction devices like a 3D tablet.

Discussion

Generating sophisticated renderings of voxel data is a well known task but there are two problems. First, creating high quality renderings requires high computational effort. Therefore we have to be content with draft quality during interaction and production quality pictures for documentation purpose. Second, rendering parameters are too formal for convenient use by physicians. We use a tree like request structure for rendering and segmentation which is formal enough for algorithmic evaluation and is suitable for user interaction because of its easy semantics and graphical representability. However, the problem of dissection remains. 3D connected component labeling seems to be a convenient tool because of its efficiency and easy semantics. The latter is most important when used by people not familiar with the mathematical background of segmentation algorithms. Another easy useable segmentation tool may be cluster analysis specially for multidimensional data. Nevertheless, manual controlling of dissection is necessary. The concerning problems of full automatic approaches are often underestimated.

At the moment there is one major disadvantage of biopsy planning: 3D vessel reconstructions are rarely available. But there are two hopeful approaches: first, 3D reconstructions of multiplanar digital angiography data and second, the use of magnetic resonance angiographic slice data. The first may lead to higher resolution and therefore to more precise planning. It has the disadvantage that it is represented in most cases in a geometrical form which cannot be integrated directly into the current modelling system. These disadvantages occur not when using magnetic resonance angiography data. But, the resolution of that material is still low therefore advanced volume rendering techniques should be applied for visualization.

Viscerocranial planning not only needs topological but also geometrical planning methods. Functions to extract the necessary geometrical information from the XCE representation should be provided. Although the total processing time which can be achieved could be reduced to 15 minutes after CT acquisition, realtime capabilities of the planning tools were quite a problem. But we hope to avoid this bottleneck by some program optimizations and the use of the next 40 to 100 MIPS workstation generation.

Acknowledgement

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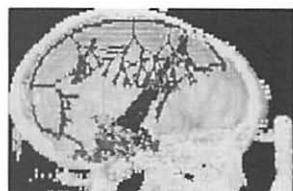
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(2) Bone, vessels and muscle tissue



(3) 90% dose volumes, tumor and bone



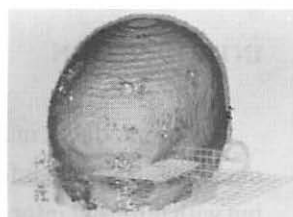
(4) "Cone of risk" and its intersections with an artificial vessel system



(5) Application of a drill during the interaction phase



(6) Result of the milling tool



(7) Simultaneous application of several saws to cut a segment out of the skull



(8) Segmented skull after several cut operations



(9) Local coordinate system of a bone segment



(10) Simulation result of a readjustment osteotomy

A Registration Technique to Integrate Information From SPECT and MR Images of the Heart

Tracy L. Faber, Roderick W. McColl, Roger M. Opperman, et al

University of Texas Southwestern Medical Center at Dallas,
Dallas, TX

SUMMARY

Methods were developed for the registration of gated three-dimensional MR and SPECT cardiac images. Left ventricular surfaces were automatically detected in the end diastolic frame of both data sets, and the best translational and rotational transform between these surfaces was determined. The transform was applied to the original SPECT image. The registered data sets were displayed by overlaying the gray scale MR image with hues related to the intensity of the SPECT image.

INTRODUCTION

Multimodality image fusion is a tool for combining the information from one image with the information from another. Two images of the same object, but with different information content are globally matched, or registered, so that the structures within overlap exactly. The data in both can then be better integrated and compared.

In medical imaging, often the information in one picture is primarily structural, while the other picture contains functional data. Registration of the images allows structure to be correlated with function. In this study, we used magnetic resonance (MR) images that contained high resolution information about left ventricular (LV) structure and motion, and single photon emission computed tomographs (SPECT) that contained lower resolution information about myocardial perfusion. When two such images are registered, the exact anatomical location of a perfusion abnormality can be identified, and structural effects can be observed.

One approach to the image fusion problem has been the use of external fiducial markers that can be seen in both pictures. The markers may be automatically or interactively identified, and the linear transform between the two sets can be determined. Similarly, internal identification points may be found in each image and matched with each other, e.g., [1].

A second approach is to find entire object boundaries in the images and to register these. The registration techniques vary; recently published methods include principal axes [2], cost minimization [3], and elastic matching [4]. The direct approach of user-interactive registration of the images themselves has also been attempted [5].

Most of the previous work has focused on neurological images. Because the brain does not move appreciably within the skull, external fiducial markers or the outer skin surface boundaries may be matched with each other. Cardiac images pose a special problem, however. Registration of external skin markers or surfaces does not guarantee registration of the heart within the body, since its position changes with body position (e.g., prone or supine), respiration, and cardiac contraction. Therefore, the hearts themselves must be specifically registered. The following sections describe one approach for performing this task.

METHODS

Four patients were imaged with MR spin-echo sequences obtained with a repetition time equal to cardiac cycle length and an echo time of 30msec. A repeated multislice or rotation technique was used to obtain images in each of 10 slices at 5 different points in the cardiac cycle. The resulting image resolution was 1.7mm in the imaging plane; slices were 10mm thick. Two SPECT studies of the same patients were obtained. The patients were injected with Tc-99m methylisobutylisonitrile (MIBI) following treadmill exercise, and also during rest. MIBI is a new myocardial perfusion agent whose radioactive properties permit gated SPECT. In this case, sixteen time frames per cardiac cycle were obtained. Reconstructions were created with filtered backprojection using a Butterworth filter of order 4 and cutoff of 4.2mm. The resolution of the resulting reconstructions was ~5mm in each plane.

We applied an automatic surface detection algorithm to both the MR and the SPECT images [6,7]. The output of this surface detector was a set of 288

points on the endocardial surface of the LV for each frame of the cardiac cycle. The points were triangulated to create closed polygon representations of the LV. The end diastolic time frame was determined using volumes computed from the polygons.

Spatial registration was accomplished by matching the detected LV boundaries at the end diastolic frame. The matching operation minimized the average distance between the two surfaces over x, y and z translations and rotations. First, the two surfaces were normalized to the same scale using their pixel sizes. They were also registered by their centers of mass. Then, for each point (a) on the SPECT surface, a line was drawn through that SPECT point and the center of mass (c) of the MR LV. Such a line intersects the MR LV at two points. Because the LV is approximated with triangles, the intersection (b) of the line ac and the triangle nearest to a can be found. Also, the distance from SPECT point a to the triangle intersection point b can be computed; this was considered to be the distance between the two surfaces at a. Figure 1 depicts this operation graphically.

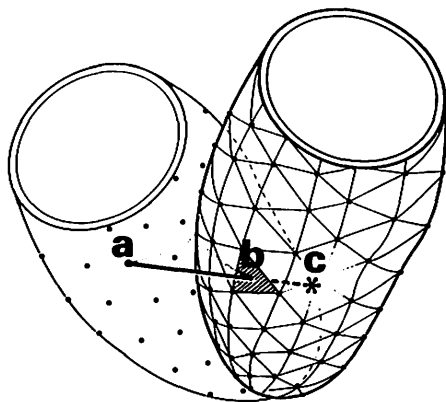


Figure 1. SPECT LV surface is depicted as the set of points on the left. MR surface is the triangulated surface on the right. The distance between the two surfaces at SPECT point a is the distance along line ac from a to b.

The average distance over all SPECT points was computed. This distance between the two surfaces is a function of x,y,z translations and rotations, and its minimal value should occur when the SPECT image is translated and rotated to match the MR exactly. We used the iterative technique of [8] to minimize the distance function. Iterations were stopped when the function cost decreased by less than 5% from the previous iteration.

A linear transform was computed from the translations and rotations and applied to the end diastolic SPECT image. The results were displayed concurrently by overlaying the MR with the SPECT. The gray level of the MR was used to define the intensity for each pixel of the composite image. The gray level of the SPECT was used to define the hue for each pixel of the composite image.

RESULTS

For the seven cases, the average distance between surfaces after registration was 2.5mm; the minimum and maximum were 1.9 and 2.9mm, respectively. Average time for all iterations was ~5min. One case is shown in detail in Figures 2-4. Figure 2 shows the two surfaces prior to registration. Figure 3 shows the surfaces after registration. Note that in both of these figures, the surfaces have already been scaled and registered by their centers of mass. The fusion operation is shown in Figure 4. From left to right, the MR, SPECT, and combined images are shown. Note the perfusion abnormality seen on the lateral wall of the LV in the SPECT image and the marked thinning of the myocardium at the corresponding point in the MR image.

DISCUSSION

This technique follows that of [3] closely. However, the cost function which they described requires the surface points to lie as contours in parallel planes. The coordinate system that we used for edge detection does not guarantee this. Instead, we implemented a cost function that was more appropriate for our 3-d surface data. We also coupled the registration process with automatic surface detection.

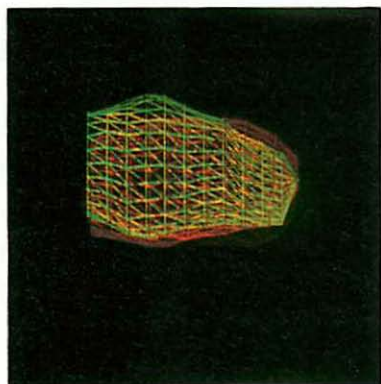


Figure 2. Relationship between SPECT (red) and MR (green) LV surfaces before registration.

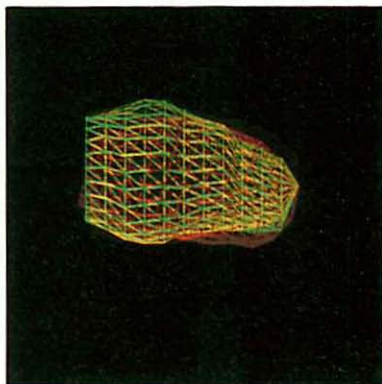


Figure 3. Relationship between SPECT and MR LV surfaces after registration.

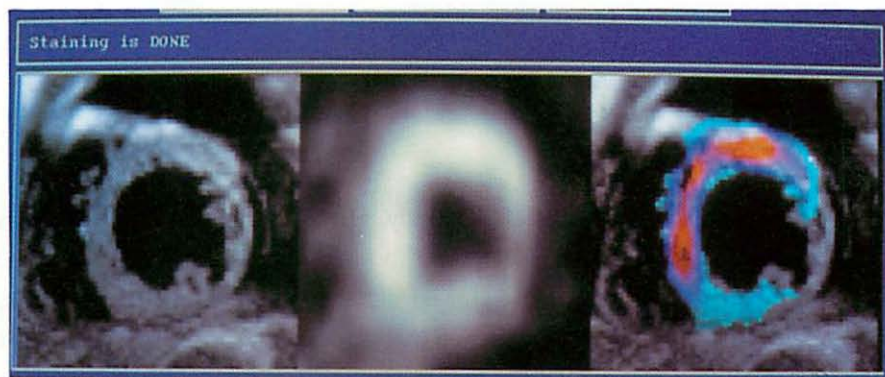


Figure 4. One slice of a cardiac MR image (left). Corresponding slice from the registered SPECT image (center). Fused image combining the MR and SPECT (right).

The registration errors that we obtained in this study were in most cases larger than those seen in reports of neurological fusion techniques. This can be attributed to a number of factors. The surface detection must be accurate, or the distance function will not necessarily reach a minimum when the two images are optimally registered. Point spread function and partial volume effects degrade SPECT images of thin structures such as the myocardium more than large structures such as the brain. Therefore, LV surface detection is more likely to be inaccurate. The calibration of pixel size must be correct, for images cannot be rescaled to improve registration. Scaling could be added to the minimization only if temporal resolution were improved enough to trust that size differences between SPECT and MR LVs were not due to mismatches in the cardiac cycle.

Nevertheless, the quantified errors in the seven studies considered are encouragingly low. The fused images also appear qualitatively accurate.

CONCLUSION

We conclude that this technique is a useful approach to three-dimensional image registration. With this method, cardiac function and structure can be more easily and more accurately correlated and compared.

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Image Filtering

Experience with Adding a Graphical User Interface to an Existing Image Processing Toolkit

E. Kaminer, M.E. Noz and J.J. Sanger

Department of Radiology, New York University, New York, NY

G.Q. Maguire, Jr.

Department of Computer Science, Columbia University,
New York, NY

Since the introduction of the Apple MacIntosh Computer, large numbers of users have experienced the ease of a "point and click" windowing system. It now seems that overwhelming demand by users is prompting an industry shift toward graphical user interfaces. We have developed a graphical user interface for our existing image processing software.

For the past ten years, we have been involved in the creation and use of software modules, known collectively as *qsh*. A description of the image format used by *qsh* and its use in application programs has been published.[1] This work is similar to what the later Utah Raster Toolkit[2] has provided for eight bit gray scale and twenty-four bit real color raster images. *Qsh* applies to a broader range of images and can be easily adapted to any standard format which is adopted in the future.

The format of images is a very important consideration, because each device that needs to manipulate them needs to know the file format. Additionally, it would be convenient if the file format chosen could also act as a database for the data associated with the image. We developed *qsh* with both of these issues in mind.

An adaptation of the AAPM standard image format[3] was used for the image file structure and the University of North Carolina (UNC) *vsh* (visual shell)[4] was used as a model for developing the image analysis software. *Qsh* is a hardware independent system, written in C and running under UNIX¹ (and VMS²) which routinely handles the standardization of image data across modalities as well as across manufacturers' diverse formats.[5]

The image file format associated with *qsh* provides: 1) a header file in text file form that contains sets of key-value pairs for the non-pixel data; and 2) a separate file composed of the N-dimensional array of numeric values (image data) which comprise the actual pixel values. The keys used are derived from the following: AAPM,[3] ACR-NEMA 300,[6] and COST-B2 Nuclear Medicine group in Europe.[5]

The header information (the key-value pairs) are stored as ASCII character strings, with a key beginning a line, possibly with leading spaces or tabs, followed by a colon equal (:=), followed by the value (in ASCII) and terminated

¹UNIX is a registered trademark of AT&T.

²VMS is a trademark of Digital Equipment Corporation.

```

Pixel Format :=
Bytes per pixel :=
Number of dimensions := N
Size of dimension [0] :=
Size of dimension [1] :=
:
Size of dimension [N-1] :=

```

Table 1: QSH Header: Required Keys

by a newline character. Table 1 illustrates those key value pairs which are essential for reading the image. Two routines, ImagePutValue and ImageGetValue are the only routines necessary to use the key-value pairs. Given a key as a string, the ImageGetValue function returns the value string by reference along with a status. If the user wishes to interpret this string as a number, it can be converted to a number (integer, float, double, ...) by standard C library routines.

Thus key-value pairs have the same behavior as LISP properties. The key-value pairs are unordered, they are created the first time ImagePutValue is given the key string, and a key retains the value given by last ImagePutValue for this key.

A server or other process can read values from a header file, answer requests for values, updates values, add new key-value pairs and update image header files. If the key "Number of dimensions := " is set equal to "0", then only a header file is expected. This provides facilities similar to environment variables (which many operating systems provide) with the added power of being able to update these values and share them between separate processes. Typical values which users might want to update and share are "Current color scale", "Background", "Saturation", ...

In the menu system which we have developed, we have used such a header file in conjunction with a database. The database maintains a list of projects such as monoclonal studies for colo-rectal cancer, or activation - reactivation Alzheimer study. When a particular project is selected, a pre-defined set of analysis tools as listed by the header file for that project are available to the user. A typical project header file is shown in Table 2. By providing a set of default values such as image placement, color scales, background, textual labels, ..., we expedite the analysis process.

Additionally, the database contains the available subjects for each particular project. The images associated with these subjects may be subcategorized by modality, i.e., SPECT, PET, MR, CT. All the images of a particular subject are grouped together. This is shown in Table 3. The image file headers associated

```

Number of dimensions:=0
Number image type labels:=4
Number of screen positions:=2
Image type label[0]:=SPECT
Image type Y_Location[0]:=0
Image type X_Location[0]:=0
Image type Y2_Location[0]:=128
Image type X2_Location[0]:=0
Screen position image one[0]:=1
Screen position image one[1]:=3
Reverse order flag[0]:=0
Image type label[1]:=STRUCTURE
:
Number landmark select labels:=6
Landmark select label[0]:=SPECT-Structure Select
:
Number landmark call back labels:=6
Landmark call back label[0]:=Slct ldmks Image One
:
Number warp select labels:=3
Warp select label[0]:=SPECT-Structure
:
Number warp call back labels:=3
Warp call back label[0]:=Warp Image One
:
Number display labels:=11
Display label[0]:=View Name
:
Number processes:=9
Process label[0]:=Choose Landmarks -STRUC
:
Number ROI label types:=2
Number ROI labels[0]:=18
Number ROI labels[1]:=15
ROI designation[0]:=Basal ganglia
:
ROI labels[32]:=rt_hemisphere

```

Table 2: A Typical Project Header File

```

%project Hemangioma
%name Subject1
    /u2/heman/sub1 CT
    /u2/heman/sub1sp SPECT
    /u2/heman/sub1nmr32 NMR

%project Dementia
%name Subject1
    /u2/dem/sub1nmr STRUCTURE
    /u2/dem/sub1t2 PRO2
    /u2/dem/sub1t1 SPECT
    /u2/dem/sub1m MARKERS

```

Table 3: A Typical Database Entry

with each image for a particular subject can be used to provide default values, as illustrated in Table 4, which can be modified by the user at run time. This gives the user a great deal of flexibility. Both the image header values and the database can be updated as necessary without the necessity of re-compiling the menu system. Once the project and the subject(s) have been chosen, the user is presented with menu choices for categories of functions. When a particular process is chosen, appropriate windows appear on the screen which allow the user to perform the indicated operations using an interactive device such as a mouse.

The menu/window system used in this manner differs from either shell scripts or protocols. The latter two are essentially one-dimensional in that the order of procedure calls and all the choices therein must be defined beforehand. The former, however, is two-dimensional in that the order of procedures can be altered as needed and more appropriate choices can be made as the process continues. There is no need to halt processing in order to re-define any procedures or variables. This can be stated succinctly by saying that rather than being asked questions in a linear order, all the settings can be altered in any order the user finds convenient.

A general purpose display window, shown in Figure 1 is provided in which the user can view images by clicking on slice increments or entering a slice number in a text window. Window width and level along with the starting position on the display screen can be chosen in the same manner. Background and saturation values can be changed with sliding scales, and color scales can be chosen from a pop-up menu. Information about the study such as subject name, exam date, body section, modality, is read from the image header and displayed in text boxes. Information relative to the final display, such as the

```

Pixel format:=8
:
Patient Name:=Subject1
Patient ID:=23456
Body section:=abdomen
Modality:=CT
Original View Name:=subject1
Pixel size[0]:=15.0
:
Color scale:=Black_and_White
Background(%):=14
Saturation(%):=98
Level:=1051
Window width:=251
Transformation Slice[0]:=4
Slice Designation[0]:=doublehemangioma
Transformation Slice[1]:=9
Slice Designation[1]:=renal vein

```

Table 4: Typical Image Header Files

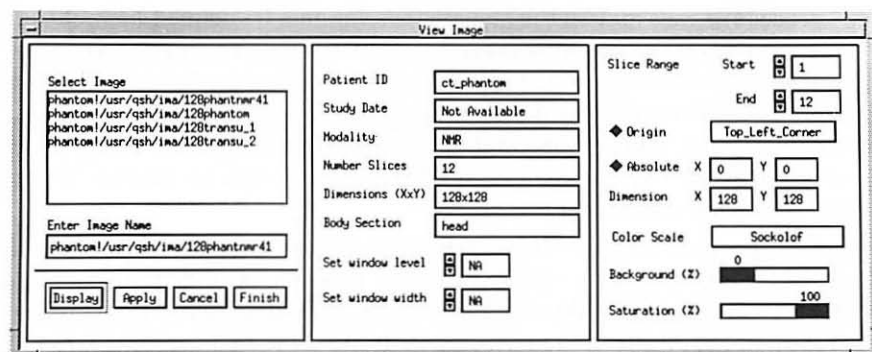


Figure 1: General Purpose View Selection Window

chosen color scale, is written to the image header for later recall.

Another menu selection as shown in Figure 2, allows multiple images to be viewed together (such as different modality images, e.g. PET, CT, MR, or images taken at different times) in order to select corresponding slices. Color scales, etc., can be individually chosen for each slice or chosen for all slices at once. Similarly, slice selection can be incremented or decremented (i.e., moved up or down through the body section) separately or together. A slice designation (such as basal ganglia level) as well as all the other information such as slice number, background, saturation, optimal color scale, can be written to each image header at will. This can be repeated as often as desired for multiple slice selection.

Another menu selection produces a window which allows the recomposition of the display screen with previously selected slices, color scales, etc., for various analysis purposes such as region of interest drawing (ROI), oblique slice reprojection, landmark selection, image warping and statistical calculation. Windows for each type of analysis lead the user through the particular steps to be performed, i.e., the tools provided are preselected for each project. Figure (3a) shows a display configuration window, while Figure (3b) shows an analysis window.

Physician acceptance has been very enthusiastic. Essentially, the windows have the easy-to-use Microsoft³ Presentation Manager interactive behavior and a distinctive three dimensional appearance.

This system is implemented using the X Window System⁴ Version 11, Release 3 with the OSF/Motif⁵ graphical user interface. We chose Motif because of its similarity to the Apple Macintosh and the Microsoft windows which were already familiar to our staff. Motif is supported by many computer system manufacturers including Digital Equipment Corporation and Hewlett-Packard Company. It is completely implemented in C and we expect no trouble in adapting our work to other interfaces such as Open Look. Only the X Window System display screen need be specified; in this particular implementation, the binaries are executed on a SUN 3/180 workstation whereas the user can be seated at a SUN workstation, a Hewlett-Packard workstation or an X terminal.

A display sub-library completely implemented in Xlib (so that frame buffers or graphics hardware supporting the X Window System can be used) has also been implemented. This is in addition to display sub-libraries which support the following displays: BarTech TVN256, TVN512; Grinnell 270; Hewlett-Packard 978010, -20, -30; Lexidata 3400, 3700; NeWS; Pixar Image Computer; Ramtek 9050, 9400; and Silicon Graphics 2400, 4DG, 4DGT.

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³Microsoft is a U.S. registered trademark of Microsoft Corporation.

⁴X Window System is a trademark of the Massachusetts Institute of Technology.

⁵OSF, OSF/Motif and Motif are trademarks of the Open Software Foundation, Inc.

Select Slices - HIV Project	
Select Slices	
PR02 Slice Number	5
STRUCTURE Slice Number	9
SPECT Slice Number	15
MARKERS Slice Number	15
All Slices	+1
Color Scale Warmbody Background (%) 0 Saturation (%) 100 Enter Slice Name Level of balls Finished Cancel Subject name ct_phantom Window Width(s) and Level(s) Level 1080 Width 80	
Select Color Scales	
PR02	
Color Scale	Heated_Body
Background (%)	2
Saturation (%)	45
STRUCTURE	
Color Scale	Black_and_White
Background (%)	12
Saturation (%)	100
SPECT	
Color Scale	Sokolof
Background (%)	0
Saturation (%)	91
MARKERS	
Color Scale	Blue
Background (%)	0
Saturation (%)	89



Figure 2: Slice Selection Window

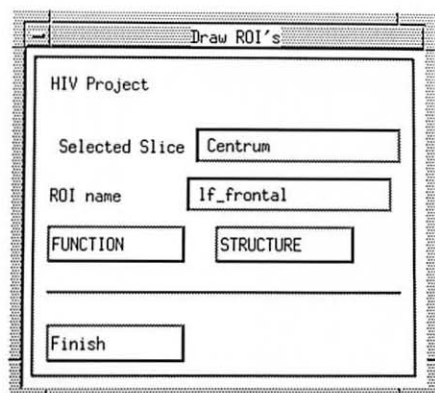
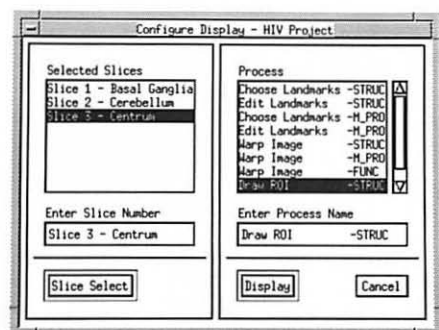


Figure 3: (a)Display Configuration Window (b)ROI Drawing Window

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Tissue Boundary Refinement in Magnetic Resonance Images Using Contour-Based Scale Space Matching

S.V. Raman, S. Sarkar and K.L. Boyer

Department of Electrical Engineering, The Ohio State University,
Columbus, OH

Abstract

Precise analysis of structures or lesions is required from cerebral magnetic resonance images for statistical studies of possible relationships between structural malformation and neuropsychiatric disorders. While individual delineation of such image features by human operators is very cumbersome, tissue boundaries in magnetic resonance images can be identified as photometric edges in the visual representation. Many edge detection filters incorporate a scaling parameter allowing a tradeoff between edge localization and error rate. In contrast to the point based scale space searching that has been proposed, we have developed a novel, whole contour based technique for tracing edges selected at a coarse scale into successively finer scales to recover the needed precision. We present a rigorous approach to setting the refinement schedule (quantizing the scale space) according to the information redundancy between adjacent filters by defining a broadly applicable similarity functional. We present experimental results on real data and outline other potential applications.

I. Introduction

In view of the ever-growing applications of magnetic resonance imaging to non-invasive examination of internal structures [1, 2, 3], the need for objective, accurate structural determinations and image analysis is apparent. In detailed analyses of subtle features, manual methods become tedious and imprecise. Applying computer vision to MRI images may prove expedient in assimilating the vast amount of data. A qualitative connection between schizophrenia and enlarged ventricles [4] has been found. To quantify this, one needs to acquire a large amount of data for a statistically significant conclusion. This is very slow and inefficient if done manually.

The most useful semantic representation of a magnetic resonance image is a description of the tissue boundaries, which may be detected as photometric edges using, for example, the Laplacian-of-Gaussian (LoG) operator. The LoG has a scale space constant, σ , which determines the degree of edge resolution. For relatively large values of σ , the edges depict the image contours in a coarse manner. Although the significant contours are represented without much superfluous detail, the existing edges provide only a rough, imprecise outline. As σ is reduced, edge accuracy improves, but this is accompanied by an increased number of spurious edges, cluttering the image. We require an algorithm incorporating both the compactness of a coarse scale representation with the precision of a fine scale edge map.

The motivation for tracking edges through scale space stems from the premise that, as shown by [5], pixels do not migrate further than two units per unit change in scale parameter. Bergholm proposes a point-based algorithm for "edge focusing", resulting in contours at a given stage representing a refinement

of the previous image within 1-pixel windows around all edge points. This method, however, leads to unnecessary noise in the final image because all edge segments near old edges are kept, regardless of their correspondence to old edge segments. Also, the migration rate assumption breaks down at very fine scales: pixels move more rapidly than predicted. Bergholm sets $\Delta\sigma = 0.7$ for $\sigma > 2$ and $\Delta\sigma = 0.3$ for $\sigma < 2$, but he does not employ a rigorously defined schedule.

We present an algorithm which automates the process with high accuracy. The algorithm refines the boundaries of the important brain structures, detected at a coarse scale, by following their progress through the scale space, enabling us to delineate them very precisely. Ours differs from other edge refinement algorithms in that it considers entire contours, not their constituent pixels, giving increased robustness in the presence of noise. The refinement schedule is also established from rigorous theoretical underpinnings. Lastly, this algorithm could allow the user to focus on a few contours of interest, since a practical image analysis tool would probably incorporate some sort of contour selection capability.

Successively refined edge representations in scale space correspond to increasingly accurate depictions of the actual contour. So for a given contour, the edge description at one level of resolution will not be dramatically different from that of the same contour at a slightly finer scale ([6]). Although any particular point may fluctuate rapidly, the net effect is minimal. Coarser regions of the scale space produce smoother contours, which are locally more nearly straight; thus, greater detail at finer scales requires more pixels to represent that detail. In view of this, we choose to follow sets of points, or contours, instead of individual pixels.

One might consider an attribute-based method, but this is inadequate because it lacks robustness and it fails to handle split and merge events. The algorithm we present uses only the property of limited pixel migration, and no explicit, whole contour attributes. The focusing routine compares contours from one level in scale space to those in another by directly calculating a "degree of relatedness" between them. This number is based on a normalized difference in pixel positions, where consensus built from the votes of individual pixels determines how well the two contours match one another. If the degree of relatedness is sufficiently large, then the contour at the finer scale must correspond to the contour at the coarser scale, and the new contour is kept. The final product is an image consisting only of fine scale contours directly descended from (selected) initial coarse scale edges.

II. The Similarity Functional

In edge refinement we have to go through the scale space from coarse to fine, as quickly as possible with the fewest possible errors. For any matching process, one must choose a next scale of the edge operator such that the contour gross shape is relatively stable and individual edge point migration is not excessive. If we take very small steps then the contours will not move much, but the process of focusing will take a long time. A very large step can introduce large changes in the contour, requiring a complicated, inefficient matching process. Our matcher, while accommodating splits and merges, nonetheless assumes the degree of individual edge point migration between scales to be limited. If the edge detectors at two scales are similar, their responses, i.e. the edge contours, will also be quite similar, and *vice versa*. So we define the *similarity* parameter, (Σ), as a functional which measures the expected degree of similarity in the output of the edge detector at two different scales. It is based on the

cross spectral density of the response at two different scales. This similarity functional then sizes our steps through scale space.

Let the edge operator impulse response at two different scales, σ_1 and σ_2 ($\sigma_1 > \sigma_2$) have Fourier transforms given by $H_{\sigma_2}(f)$ and $H_{\sigma_1}(f)$, respectively. The cross spectral density of the outputs when driven by white noise is given by $S_{H_{\sigma_2}H_{\sigma_1}}(f) = H_{\sigma_2}(f)H_{\sigma_1}^*(f)$ where the $*$ superscript denotes complex conjugation. We define similarity by:

$$\Sigma(H, \sigma_2, \sigma_1) = \frac{\int_{-\infty}^{\infty} S_{H_{\sigma_2}H_{\sigma_1}}(f)df}{\sqrt{\int_{-\infty}^{\infty} S_{H_{\sigma_2}H_{\sigma_2}}(f)df \int_{-\infty}^{\infty} S_{H_{\sigma_1}H_{\sigma_1}}(f)df}} \quad (1)$$

$\Sigma(\bullet, \bullet, \bullet)$ is the integral of the cross spectral density, normalized by the square root of the product of the spectral densities of each filter. Note that when $\sigma_2 = \sigma_1$, $\Sigma = 1.0$, implying identical responses, the limiting case of similarity. When the frequency response of the two edge operators are such that they do not overlap at all, then their cross spectral density is zero and so is the similarity.

When entering the image to be processed, the user also sets a constant value for similarity between two levels of σ . For high similarity values, e.g. 0.95, the schedule will consist of relatively small values for $\Delta\sigma$; that is, focusing takes place in small steps through scale space. As the similarity specification is decreased, the allowable jump size increases, but the potential information redundancy falls off. We can also set a schedule of constant step size, $\Delta\sigma$, and anticipate edge migration commensurate with the present similarity value, which would then be different at every step.

A. The Laplacian-of-Gaussian Edge detection operator

The Laplacian-of-Gaussian edge detector is expressed mathematically as

$$\nabla^2 g(x, y) = \frac{1}{2\pi\sigma^4} \left(2 - \left(\frac{x^2 + y^2}{\sigma^2} \right) \right) e^{-\frac{x^2 + y^2}{2\sigma^2}} \quad (2)$$

The LoG is a circularly symmetric operator in both the space and frequency domains. Setting Σ to a constant value, say S , letting $\sigma_1 > \sigma_2$, $\sigma_1 - \sigma_2 = \Delta\sigma$, and denoting σ_1 by σ , the value of the current scale, we get a relationship between the size of the step we want to take at a particular scale and the value of the current scale:

$$\frac{\Delta\sigma}{\sigma} = \left(1 - \frac{k_{LoG} - \sqrt{k_{LoG}^2 - 4}}{2} \right) \quad k_{LoG} = (2/S^2) \quad (3)$$

Equation (3) relates three parameters: the present scale, σ , the next scale step, $\Delta\sigma$, and the similarity, S . In matching we can fix either of two parameters: $\Delta\sigma$ or S . The starting value of σ (say σ_0) is also specified as well as some stopping criterion.

If $\Delta\sigma$ is fixed our matching process has to expect changes according to the similarity value, itself a function of the present σ . Fig. 1(a) is a plot of the similarity functional versus the present scale. Each curve corresponds to constant step size. For a specified step size, the focusing process operates along one of these curves. Given the present scale, σ , we have a measure of the expected similarity of the filter response at the next scale, $\sigma - \Delta\sigma$. Our selection of $\Delta\sigma$ in the constant step size approach is constrained by the smallest desired scale of the refinement process. We choose the largest step, using the curves

in Fig. 1(a), such that the similarity will not go below some lowest similarity that can be tolerated by the matching process (typically 0.8 for our algorithm). Also, when choosing a starting point, one must determine if: all contours of interest are at least coarsely represented, and the image is sufficiently noise-free to minimize the perpetuation of unimportant initial edges. The path marked with arrows in Fig. 1(a) is one of the schedules followed by Bergholm [5]. Note that Bergholm had to take smaller steps after $\sigma = 2.0$ because the similarity value would have decreased further making the matching prone to error; however, he did not quantify this effect as we have.

Another parameter which we can specify in Equation (3) is the similarity while $\Delta\sigma$ varies. This ensures consistent matching reliability. For constant similarity, S , the ratio of the step size to the present scale, $\frac{\Delta\sigma}{\sigma}$, is constant. This ratio is a function of the chosen similarity, giving a second operating characteristic. Given the minimum similarity we can tolerate, we select the ratio $\frac{\Delta\sigma}{\sigma}$. The step size is then proportional to the present σ , which agrees with intuition.

B. The zero crossing operator of Sarkar and Boyer

We now develop the scheduling relationship for the *better* (indeed optimal) edge detection operator suggested by Sarkar and Boyer [7].

The operator impulse response is given by:

$$h_{\gamma}(x) = A \left(1 + \frac{\alpha}{\gamma}|x| - \frac{\alpha+1}{2} \frac{x^2}{\gamma^2} \right) e^{-\frac{|x|}{\gamma}} \quad -\infty < x < \infty \quad (4)$$

γ is a scaling parameter analogous to σ for the LoG. As γ is increased the spatial extent of the filter increases resulting in fewer spurious responses and a loss of detail and fine edge structure. Following a similar procedure in deriving Σ as was done for the LoG, we obtain

$$\Delta\gamma = \gamma \left(1 - \left(\frac{k_{SB} - \sqrt{k_{SB}^2 - 4}}{2} \right)^2 \right) \quad \text{with} \quad k_{SB} = \frac{2}{S^{\frac{1}{4}}} \quad (5)$$

This expression is similar to Equation (3); we have analogous operating characteristics and operating plots similar to those for the LoG can be made.

It is interesting to compare the curves for the LoG and the optimal zero crossing operator. Fig. 1(b) plots the ratio of the step size to the present scale against the similarity functional. Note that the curve for the optimal zero crossing operator lies above that of the LoG for all values of the similarity functional. This means that *one can take larger steps across the scale space for the optimal zero crossing operator than can be taken for the LoG.*

III. Refined Contour Selection Procedure

Our matching schedule depends on edge pixel migration being bounded for a specific change in the scale. We have noticed that Bergholm's estimate of pixel movement is valid only for $\Sigma > 0.8$ (see Fig. 1(a)). For lower similarities we observe greater average pixel migration.

At every focusing step we maintain an array, called the **match-table**. Each column corresponds to a contour from the smaller scale (σ or γ). The rows

correspond to the contours at the present scale. Each match table entry is the match factor denoting the quality of match between the two corresponding contours. Because of the pruning of the search space by the early exit condition on the distance summation, there are no entries corresponding to contour pairs having a match factor less than 0.7. The match factor is simply a warping (for human consumption) of min-d values into the range $0 \rightarrow 1$ such that 0.7 corresponds to the smallest value for a valid contour match (Bergholm's limit): 1 is a perfect match, and 0 is an impossible match.

Fig.2(a) shows the closed LoG contours detected at $\sigma = 4.5$ of a coronal MRI brain image. The same image appears in Fig.2(b), but here $\sigma = 4.0$, and several interesting changes have occurred. In the upper left hand region of the scene at $\sigma=4.5$, the contour labeled ρ lies separated from contour α (the rough cerebral outline). But in Fig. 2(b), what was ρ has now merged with the larger contour. In total, three contours at the coarser scale (α , ρ , and ϵ) merge into one, b , at the finer scale.

Table 3 is the match-table comparing Figs. 2(a) and 2(b). To check if the algorithm detects both merges, look under the column labeled "b"; indeed, there are three significantly large match-factors. The algorithm has determined that old contours α , ρ , and ϵ are now represented by new contour b . Also note that the corresponding match factors are much greater than 0.7. In the domain of pixel migration, this means that average pixel movement along the contour is much less than Bergholm's upper bound. This is encouraging because it suggests robustness with respect to noise and the threshold selection.

IV. Experimental Results

This section presents results derived from coronal magnetic resonance images. Fig. 4(a) represents a somewhat posterior section through the brain (note the presence of the cerebellum). Fig. 4(b) shows the edges detected for $\sigma = 5.0$, and Fig. 4(c) corresponds to the outline at $\sigma = 2.0$. The edges of Fig. 4(d) are those kept from $\sigma = 2.0$ after performing three edge refinement steps of $\Delta\sigma = 1.0$. Fig. 4(e) results from keeping the similarity constant (in this instance, $\Sigma = 0.8$) and allowing the step size to vary. Based on this, the schedule for σ required only two comparisons: from 5 to 3.3, and from 3.3 to 2. The resulting images are virtually identical. Clearly a constant similarity schedule traverses scale space more efficiently than a constant step size schedule.

The next series of images illustrates how the algorithm works on the same gray-level image, but with the optimal operator of Sarkar and Boyer [7]. The operator does not give closed contours like the LoG, but can traverse a broader range of scale space in fewer steps. Fig. 4(f) represents $\gamma = 3.0$, Fig. 4(g) is at $\gamma = 1.0$. Using $\gamma = 3.0$ as the starting point and $\gamma = 1.0$ as the final point yields Fig. 4(h) when applying the algorithm. Starting instead from the $\gamma = 3.0$ picture and removing one-pixel edges yields results in Fig. 4(i). The identical nature of Figs. 4(h) and (i) implies that by initially removing one-pixel contours, one eliminates a number of computations, making the algorithm more efficient without affecting the final output. An advantage of focusing using this edge detector is that a great deal of time is saved since there are no extremely long contours like those from the LoG. The time spent in distance calculation is significantly reduced.

V. References

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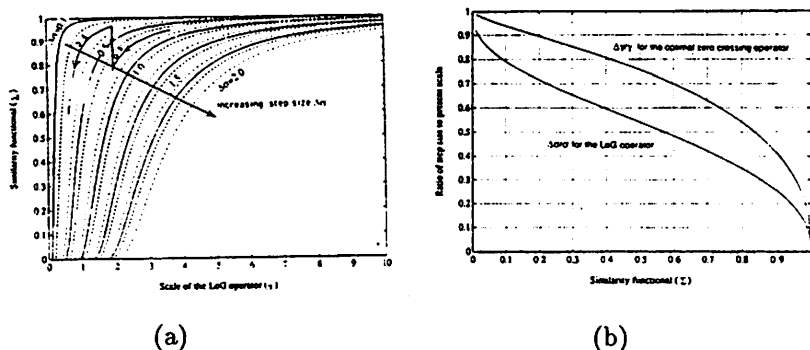


Figure 1: (a) Curves with constant steps ($\Delta\sigma = 0.1$ to 2) in scale space for the LoG operator. (b) Comparison of the Ratio of the step size and the present (σ or γ) vs. the similarity functional for the LoG and the optimal zero crossing operator of Sarkar and Boyer.



Figure 2: (a) Closed contours detected with $\sigma = 4.5$. (b) Closed contours detected with $\sigma = 4$. (c) Traced edges.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM	DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EE	EF	EG	EH	EI	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES	ET	EU	EV	EW	EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ	FK	FL	FM	FN	FO	FP	FQ	FR	FS	FT	FU	FV	FW	FX	FY	FZ	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ	GK	GL	GM	GN	GO	GP	GQ	GR	GS	GT	GU	GV	GW	GX	GY	GZ	HA	HB	HC	HD	HE	HF	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	HV	HW	HX	HY	HZ	IA	IB	IC	ID	IE	IF	IG	IH	II	IJ	IK	IL	IM	IN	IO	IP	IQ	IR	IS	IT	IU	IV	IW	IX	IY	IZ	JA	JB	JC	JD	JE	JF	JG	JH	JI	IJ	JK	KL	JM	JN	JO	JP	JQ	JR	JS	JT	JU	JV	JW	JX	JY	JZ	KA	KB	KC	KD	KE	KF	KG	KH	KI	KJ	KK	KL	KM	KN	KO	KP	KQ	KR	KS	KT	KU	KV	KW	KX	KY	KZ	LA	LB	LC	LD	LE	LF	LG	LH	LI	LJ	LK	LL	LM	LN	LO	LP	LQ	LR	LS	LT	LU	LV	LW	LX	LY	LZ	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	ML	MM	MN	MO	MP	MQ	MR	MS	MT	MU	MV	MW	MX	MY	MZ	NA	NB	NC	ND	NE	NF	NG	NH	NI	NJ	NK	NL	NM	NN	NO	NP	NQ	NR	NS	NT	NU	NV	NW	NX	NY	NZ	OA	OB	OC	OD	OE	OF	OG	OH	OI	OJ	OK	OL	OM	ON	OO	OP	OQ	OR	OS	OT	OU	OV	OW	OX	OY	OZ	PA	PB	PC	PD	PE	PF	PG	PH	PI	PJ	PK	PL	PM	PN	PO	PP	PQ	PR	PS	PT	PU	PV	PW	PX	PY	PZ	QA	QB	QC	QD	QE	QF	QG	QH	QI	QJ	QK	QL	QM	QN	QO	QP	QQ	QR	QS	QT	QU	QV	QW	QX	QY	QZ	RA	RB	RC	RD	RE	RF	RG	RH	RI	RJ	RK	RL	RM	RN	RO	RP	RQ	RR	RS	RT	RU	RV	RW	RX	RY	RZ	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ	SK	SL	SM	SN	SO	SP	SQ	SR	SS	ST	SU	SV	SW	SX	SY	SZ	TA	TB	TC	TD	TE	TF	TG	TH	TI	TJ	TK	TL	TM	TN	TO	TP	TQ	TR	TS	TT	TU	TV	TW	TX	TY	TZ	UA	UB	UC	UD	UE	UF	UG	UH	UI	UJ	UK	UL	UM	UN	UO	UP	UQ	UR	US	UT	UU	UV	UW	UX	UY	UZ	VA	VB	VC	VD	VE	VF	VG	VH	VI	VJ	VK	VL	VM	VN	VO	VP	VQ	VR	VS	VT	VU	VV	VW	VX	VY	VZ	WA	WB	WC	WD	WE	WF	WG	WH	WI	WJ	WK	WL	WM	WN	WO	WP	WQ	WR	WS	WT	WU	WV	WW	WX	WY	WZ	XA	XB	XC	XD	XE	XF	XG	XH	XI	XJ	XK	XL	XM	XN	XO	XP	XQ	XR	XS	XT	XU	XV	XW	XX	XY	XZ	YA	YB	YC	YD	YE	YF	YG	YH	YI	YJ	YK	YL	YM	YN	YO	YP	YQ	YR	YS	YT	YU	YV	YW	YX	YY	YZ	ZA	ZB	ZC	ZD	ZE	ZF	ZG	ZH	ZI	ZJ	ZK	ZL	ZM	ZN	ZO	ZP	ZQ	ZR	ZS	ZT	ZU	ZV	ZW	ZX	ZY	ZZ
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Figure 3: Match-table between the contours at $\sigma = 4.5$ (rows) and the contours at $\sigma = 4.0$ (columns). Boldface match-factors correspond to matches.

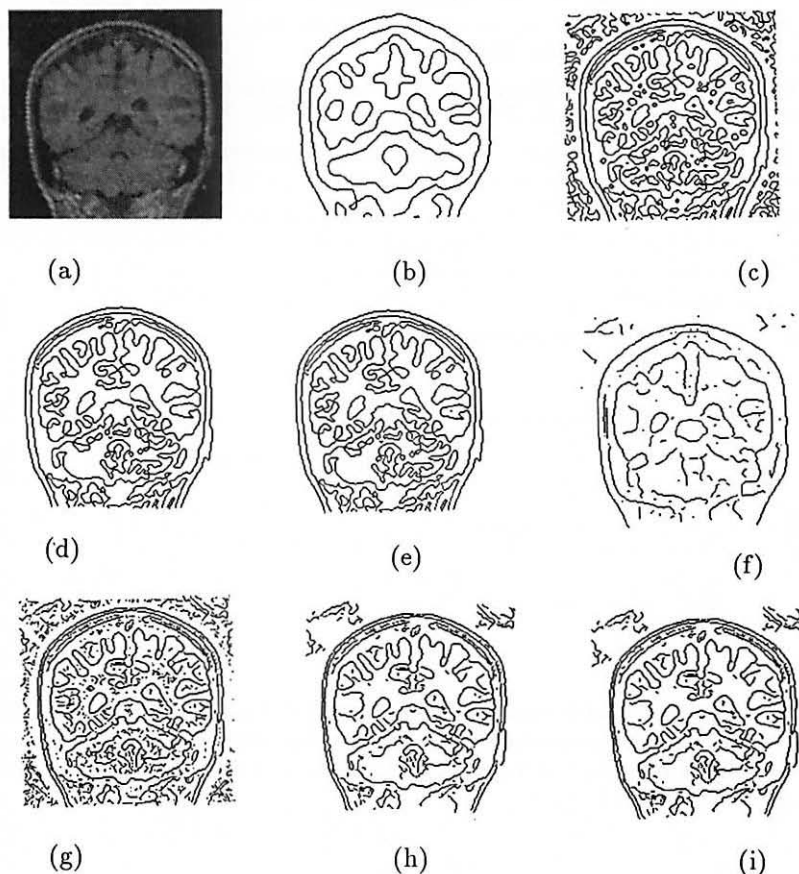


Figure 4: (a) The gray-level image of a slightly posterior section of the brain. (b) LoG at $\sigma = 5.0$. (c) LoG at $\sigma = 2.0$. (d) Traced edges with constant $\Delta\sigma = 1.0$. (e) Traced edges with constant inter-sigma similarity = 0.8. (f) Zero crossing edge detection at $\gamma = 3.0$. (g) $\gamma = 1.0$ Scale-space matching starting from (h) $\gamma = 3.0$ and (i) thresholded $\gamma = 3.0$.

Image Registration with Complex Line Moments

Giann-Tyn Hou and Oleh J. Tretiak

Image Processing Center, Drexel University,
Philadelphia, PA

Abstract. A new technique, complex line moments (CLM's), is developed for encoding linear features in images. This technique is analogous to complex moments computed from regions. An algorithm is developed for computing CLM's from chain-coded boundaries obtained from grey-value images. The accuracy of these features is investigated. It is found that this technique is effective for measuring the location and orientation (rotation) of an object.

The CLM technique is incorporated in an image registration algorithm which is capable of matching objects part of whose outlines are dissimilar. The algorithm can compute transformations between images being matched with sub-pixel accuracy. Distance transforms of both objects are used to identify portions of images that are homologous in a geometrical sense, and CLM's of the homologous portions are used to compute the displacement and rotation which will place the images into registration. Feature extraction and selection of matching portions is done automatically in an iterative algorithm. The algorithm initially operates in a tolerant mode, attempting to place all images features into registration. Subsequently, the distances between portions of the objects are used to produce increasingly stringent criteria for rejecting disparate portions of the two objects, and similar portions are registered by computing the appropriate geometrical transformation.

Experiments were performed with images of autoradiograms of successive sections of rat brains. The algorithm is capable of registering images even when parts of the outline are outside the field of view, and when the image outlines are distorted because of errors in the edge extraction procedure.

I. INTRODUCTION

In image analysis, one of the fundamental operation is the comparison of features in related images. Some examples include angiography, analysis of image sequences (cineradiology), and followup studies of a patient. In autoradiography one often needs to compare pairs of homologous images (histology and autoradiogram) or autoradiograms from serial sections [1]. Most such studies require image registration, that is, the mapping of one image to another so that homologous objects fall on corresponding coordinates, and this requires the measurement of the mapping between the coordinates in the two images. In the simplest case, this mapping is an isometry (a combination of a translation and rotation).

Correlation is the most common technique for identifying corresponding objects in pairs of images [2, 3]. Though powerful, this technique is somewhat inflexible and

requires enormous volumes of computation. Another strategy is to extract features, and to perform registration on properties of these features. One of the most common such feature sets are the moments [4]. Initially, moments were used as descriptors for pattern recognition, though they also have been applied for image registration [5, 6]. These techniques are quite effective when the object being matched have the same shape, differing only by an affine transformation. In general, the problem is much harder. Parts of the objects may be identical but other parts may differ: this may be caused by occlusions, incomplete views, or failures in delineation. Thus, in general, one must also solve the so-called correspondence problem, that is, to identify the portions that are homologous.

In this paper, we describe a technique for two-dimensional partial image registration which simultaneously solves the correspondence problem and determines the best transformation for performing the registration. The registration transformation is based on complex line moments: these are geometrical moments, such as those studied in the literature [4, 7, 8]. Commonly, moments are based on functions of two variables. In our work we compute *line moments* which are evaluated from linear structures such as edges or boundaries. The correspondence problem is solved by the use of the *distance transform*, an efficient technique for identifying which parts of two images correspond. We develop an iterative boundary matching algorithm, and present experimental results on partial image matching.

II. COMPLEX LINE MOMENTS

Assume a curve is represented by the parametric equation $(X(t), Y(t))$ for $a \leq t \leq b$. Another form of this is the complex function $Z(t) = X(t) + iY(t)$. We define the *Cartesian moments* of the line by

$$m_{pq} = \int_a^b X^p(t) Y^q(t) \frac{dl}{dt} dt$$

where

$$\frac{dl}{dt} = \sqrt{\left(\frac{dX(t)}{dt}\right)^2 + \left(\frac{dY(t)}{dt}\right)^2}$$

The *complex line moments* are defined as

$$C_{pq}[Z] = \int_a^b Z^p(t) Z^{*q}(t) \left| \frac{dZ(t)}{dt} \right| dt$$

where $Z(t) = X(t) + iY(t)$ and $Z^*(t)$ is the complex conjugate of $Z(t)$. Complex moments have the following attractive properties:

(1) Rotation Properties:

If the image $f_1(x, y)$ is rotated counterclockwise through a angle θ (or the image plane axes rotated through a clockwise angle θ) to become $f_2(x, y)$ so that $f_2(x_2, y_2) = f_1(x_1, y_1)$ where

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \end{bmatrix}$$

then the new set of Complex moments, namely C'_{pq} is related to the old by the equation

$$C'_{pq} = C_{pq} e^{z(p-q)\theta}$$

(2) Translation Properties:

If the image $f_1(x,y)$ is shifted by an amount $w=u+iv$, (or the image plane axes shifted by $-w$) to become $f_2(x,y)$, then the new C'_{pq} is given by

$$C'_{pq} = \sum_{m=0}^p \sum_{n=0}^q w^{p-m} \bar{w}^{q-n} \binom{p}{m} \binom{q}{n} C_{p-m, q-n}$$

(3) Scaling Properties:

If the image $f_1(x,y)$ is scaled by a scaling factor K , (or the image plane axes scaled by $1/K$) to become $f_2(x,y)$, then the new C'_{pq} is related to C_{pq} by the relation

$$C'_{pq} = K^{p+q+1} C_{pq}$$

The centroid of the curve can be calculated by $w_c = C_{10}/C_{00}$. The Central Complex Moments are defined by the equation

$$Q_{pq} = \int_a^b (Z(t) - w_c)^p (\bar{Z}(t) - \bar{w}_c)^q \left| \frac{dZ(t)}{dt} \right| dt$$

They may be computed by first finding the ordinary complex line moments, computing w_c from C_{10} and C_{00} as shown above, and then applying the shift property.

Suppose C_{pq} and C'_{pq} are the complex line moment of two curves that differ from each other by a combination of a rotation and translation. We may represent the transformation by a rotation about the centroid followed by a shift. The centroids of the two curves can be found from the first- and zero-order moments. The rotation can be found from the phase (argument) of the complex moments. For example,

$$\theta = \arg(Q_{21}) - \arg(Q'_{21}).$$

If, furthermore, the two curves differ by a scale factor, it can be found from the ratio of the zero order moments.

In our computer programs[9], curves were represented by chain codes. That is, the curve consisted of line segments with knots on adjacent pixel coordinates, and each chain code element is interpreted as a line segment. We compute its complex line moments from the centroid, angle, and length. The total line moments of the curve are computed just by summing the line moments of all chain code segments. Numerical trials on boundaries of geometrical figures such as rectangles and triangles indicate that the chain-code representation can affect C_{00} by as much as 20%. In spite of this, the values of centroid and orientation angle computed from the moments were sufficiently accurate to allow sub-pixel registration. We found that best accuracy in rotation angle estimates were obtained by examining both Q_{20} and Q_{21} .

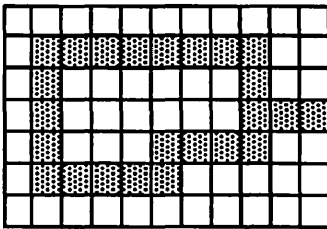
III. MATCHING PRINCIPLE AND ALGORITHM

If two curves are identical then complex line moments provide a convenient technique for finding their registration parameters. The basic idea in our work is to find those portions of two curves that are identical, and to use complex line moments to register them. Matching portions are identified by using distance functions and distance transforms. The basic idea is to find an approximate registration transformation, to identify matching parts after registration, and to recompute the registration of the matching portions. If we continue to iterate the same process several times, the final result will reach some stable or best point which may satisfy our criterion. Complex line moments are attractive because they are well adapted for partial boundary matching.

The distance function is a convenient tool for both identifying matching portions of two curves and for computing their CLM's. The distance from a set S to point x is defined as:

$$d(x, S) = \min_{y \in S} \|x - y\|.$$

When viewed as a function of x , this is called the distance function (distance transform) of set S . In our work we use an efficient algorithm proposed by Borgfors [10] that approximates the Euclidean distance for each pixel. The distance transform converts a binary digital image, consisting of feature (boundary) and non-feature (non-boundary) pixels into a gray-level image where the value of all non-feature pixels is approximately equal to three times the Euclidean distance to the nearest feature pixel. Figure 1 shows an example of the distance function computed by the Borgfors algorithm.



4	3	3	3	3	3	3	3	3	4	7
3	0	0	0	0	0	0	0	0	3	6
3	0	3	3	3	3	3	3	0	3	3
3	0	3	6	4	3	3	3	0	0	0
3	0	3	3	3	0	0	0	0	3	3
3	0	0	0	0	0	3	3	3	4	6
4	3	3	3	3	3	4	6	6	7	8

Figure 1 (a) The original image

(b) The distance function of the image

Suppose we have two sets: BA , the reference curve and BB , a control curve. The distances between points on one curve and the other curve can be easily found after we compute the distance functions of both curves. The matching portions BA' and BB' are defined by:

$$BA' = \{ x \mid x \in BA, d(x, BB) < \psi \}$$

$$BB' = \{ x \mid x \in BB, d(x, BA) < \psi \}$$

where ψ is a matching distance criterion. To decide the proper criterion ψ for rejecting the unmatched parts is tricky: if the distance criterion is too small, it is possible to reject some matched parts of the boundaries, and matching performance may deteriorate. The method used for selecting the criterion ψ is based on the maximum distance from control boundary to reference boundary ($MDBA$), which is defined by

$$MDBA = \max_{x \in BB} d(x, BA).$$

A coefficient ζ is used to multiply $MDBA$ to produce the distance criterion ψ , and this coefficient decreases slowly in succeeding iterations. The basic scheme is to gradually decrease ζ in order to avoid discarding the parts that should be considered.

The distance criterion is used directly to compute the so-called weighted line moments, defined by:

$$C_{pq}[BB'] = \int_{BB} Z(t)^p Z^{*q}(t) \omega_t(Z(t)) dt$$

where $\omega_t(z)$ is a weighting function: when computing the moments for BB' ,

$$\omega_t(z) = \begin{cases} 1 & \text{if } d(z, BA) < \psi \\ 0 & \text{if } d(z, BA) \geq \psi \end{cases}$$

The Algorithm.

The matching algorithm is a technique for finding the best transformation between boundaries in two different images. Input to the algorithm are two images with thresholds specifying the criterion for extracting boundaries. The effectiveness of matching is measured by a generalized distance function that depends on the two boundaries and the transformation. The algorithm's outline is given in Figure 2.

Step 0. INITIAL MATCHING

Step 1. IDENTIFY CORRESPONDING PARTS AND COMPUTE

Step 2. COMPUTE TRANSFORMATION.

Step 3. EVALUATE TRANSFORMED RESULT.

If termination criterion is met, STOP. Otherwise, go to *Step 1*.

Figure 2. Boundary Matching Algorithm

Step 0. The two boundaries BA and BB (the reference and control curves) are represented by two sequences of chain codes. Complex line moments up to third order are computed. The centroids are found from the zero'th and first moments, and the second and third order central complex line moments are used to get the rotation angle. INITIAL MATCHING consist of a shift and rotation of the control boundary BB according the parameters obtained from the line moments. If the boundaries are different this will not give the optimal transformation.

Step 1. IDENTIFY CORRESPONDING PARTS AND COMPUTE WEIGHTED MOMENTS. In this step we try to identify the corresponding parts of the control and reference boundaries, and these are used when we compute the weighted moments. We first compute the quantity $MDBA$ defined above from the transformed BB . This and the coefficient ζ are used to obtain the distance criterion ψ . The weighted moments of BA and the transformed BB are then computed, as described above.

Step 2. COMPUTE NEW TRANSFORMATION. As in in initial matching, the shift is found from the centroids, while the rotation is based on the second order moments. Note that this is the transformation between the *transformed* control boundary and the reference boundary, so that the full transformation is found by composing this with the transformation used to modify BB in *Step 1*. In subsequent

iterations we compute the transformed BB by applying the *composed* transformation to the initial control boundary. This is done because transformations can be composed very accurately, but iterated transformations of a chaincoded boundary produce large numerical errors because of the chaincode representation.

Step 3. EVALUATE TRANSFORMED RESULT. In this part, our objective is to examine the re-matching result and compare it with the previous one. If the new transformation does not improve the match, we discard it and go back to adjust the distance criterion ψ trying to match again. If the new result is better than the old one, we will store this result and still go back to STEP 1 trying to make the match even better. We examine *EBB*, defined by

$$EBB = \sum_{y \in BB} d(y, BA).$$

We compare the values of *EBB* before and after the iteration. If *EBB* decreases, we accept this transformation and set the iteration flag *Y* to zero. If it increases, we discard the new transformation and increment the iteration flag. The termination point is perhaps the trickiest part of the algorithm. We find that once the error function reaches some optimum value further decreases of the distance criterion ζ causes some of the valid parts of the boundaries to be rejected. The method we use is: if the iteration flag *Y* is zero, ζ is decreased and the transformation is accepted. If the iteration flag is positive but less than 4 the transformation is rejected but ζ is increased. The process stops once the iteration flag is greater than 3. This criterion is based on experimental results. We found that once the number of vain trials was greater than 3 it was unlikely that there would be further improvement.

IV. EXPERIMENTAL RESULTS

The algorithm was evaluated in controlled trials by applying it to pairs of boundaries that differed in various ways. Figure 3 shows a example of the whole matching process to demonstrate different steps of the algorithm. The reference image in Figure 3(b) and the control image, shown in Figure 3(a), have different orientations and parts of the object are missing. First pass matching, shown in Figure 3(c), is not accurate because of the missing boundary portions. Figure 3(d) is the comparison between the first pass matching and the first iteration of the algorithm, and we see the result is much closer. In following iterations matching is even better, as shown in Figures 3(e), (f) and (g). Figure 3(h) shows the final result.

V. CONCLUSIONS

The image matching technique based on line moments and distance functions proposed in this paper is a new approach to image registration. The work was motivated by the need of developing a simple and efficient method to find the best matching position of two partial images. The novel results in this paper can be divided into two parts: the development of complex line moments, and a new boundary matching algorithm.

Complex line moments enable us to work on the matching problem when only parts of the image boundary are available, so that conventional area moments cannot be applied. The use of complex line moments in place of area moments has proved to be a convenient and reliable way to solve the matching problem. Complex line

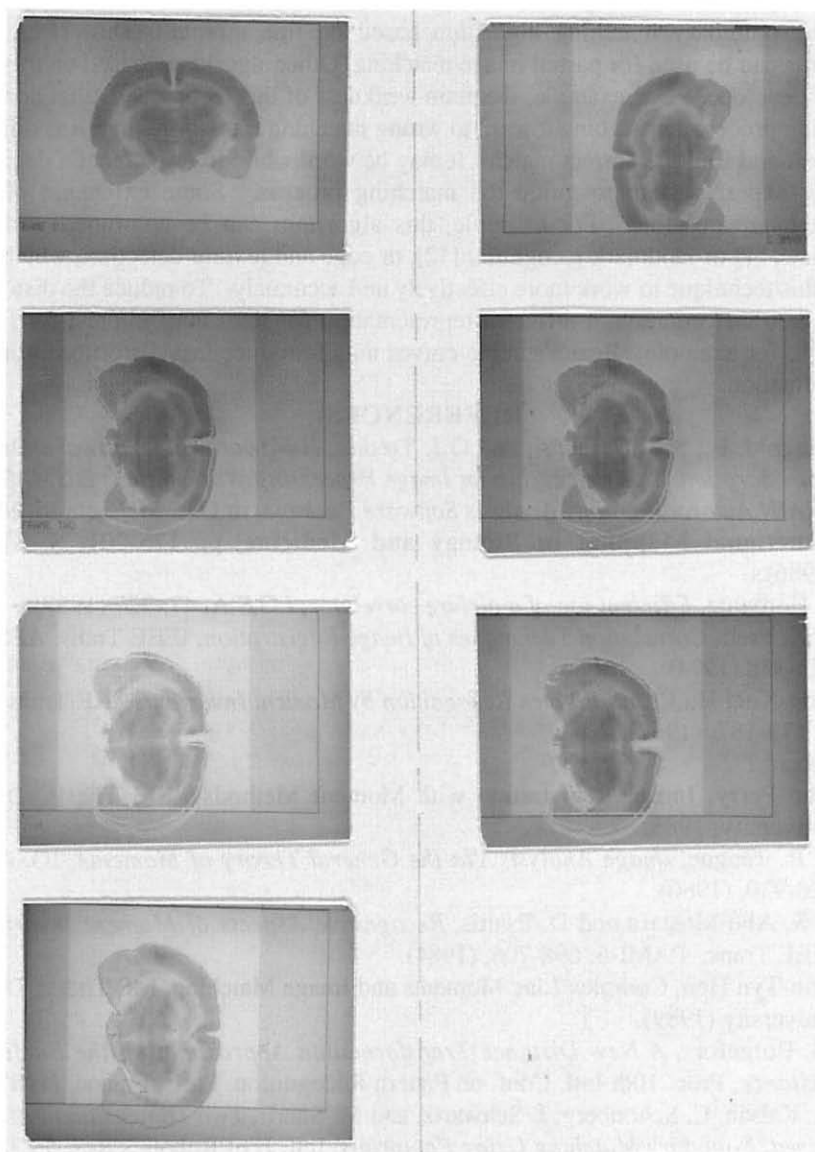


Figure 3. (left to right, top to bottom) (a) The control image and its boundary. (b) The reference image and its boundary. (c) The image after the first pass matching. (d) Comparison between the first pass matching and the first iteration. (e) The result of the second iteration is better. (f) The result of the third iteration is getting even better. (g) After several iterations. (h) The final result.

moments are computed from chain-code representations of the boundary, and we found that this limits the accuracy.

The boundary matching algorithm based on line moments shows that line moments can be used for partial image matching. Other algorithms based on this idea can be developed. For example, the main weakness of this technique is that once the matching process starts going toward to wrong matching transformation, it is difficult to retreat and find the correct match. It may be worthwhile to implement a decision-making expert system to guide the matching process. Some extension of this approach are possible. For example, this algorithm can be combined with the footprints[11] or landmark recognition[12], or edge and texture detection, which will allow this technique to work more effectively and accurately. To reduce the distortion of image transformation, a different representation for lines is of interest for future research: for example, Bezier's cubic curves may introduce less distortion in image transformation.

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Automatic Contour Generation in Binary Scenes

Klaus D. Toennies

Fachgebiet Computer Graphics, Technische Universitat Berlin,
Institut fur Technische Informatik, Berlin,
FEDERAL REPUBLIC OF GERMANY

Abstract

A triangulated 3D representation originates from contours which approximate boundaries of segmented objects in CT or MR slices. Since contours are the framework for surface reconstruction an efficient surface representation depends on efficient contour approximation. For that purpose we present an algorithm which minimizes the number of approximating line segments for a given similarity constraint. The method is based on a graph-theoretic approach where the optimal solution is a minimum cost path in a graph representing boundary points and possible line segments between such points. The optimal contour approximation is compared to two heuristic methods for fast contour approximation. The first algorithm uses the principle of extending line segments until a given similarity constraint is violated. The second algorithm creates a contour by subsequent subdivision of line segments until a certain similarity constraint is satisfied.

Introduction

3D surface reconstruction by triangulation generates triangular surfaces from polygonal descriptions of object boundaries in segmented CT or MRI images [2],[4],[7],[9]. Such images are discrete, two-dimensional scenes of picture elements (or pixels) whose values represent the parameter which is measured and reconstructed by the imaging system. A segmentation operator generates a binary scene from that image by assigning to each pixel either the value '0' (background pixels) or the value '1' (object pixels). Contours are

created from the binary image by applying boundary tracing and contour approximation.

Boundary detection traces bounding edges of object pixels which form connected sets in a binary image. Two object pixels are connected if they share at least a common vertex (there are other definitions of connectivity which result in slightly different boundary tracers). A new boundary is detected in a binary image if an unmarked transition from a background voxel to an object voxel is found while scanning the image in a line-by-line fashion. The edge at such transition is marked and stored as initial element of a new boundary. Beginning at the initial edge a loop follows where we search for the successor of the current boundary edge until the first edge is reached again. (The determination of the next boundary edge is done by looking for a background-to-object transition in the four-pixel-neighbourhood at the vertex between the current edge and its potential successor.)

Boundary tracing results in a vertex list describing boundary edges. Since the large number of boundary edges would not lead to an efficient surface representation a contour approximation step follows which removes as many vertices as possible while retaining major shape features.

Optimal contour approximation

With given vertices $V=\{v_1, v_2, \dots, v_n\}$ of a boundary we wish to select a subset $V_c=\{v_{c(1)}, v_{c(2)}, \dots, v_{c(m)}\}$ which approximates V in an optimal fashion. Optimality may be defined either as maximum accuracy to be achieved by a given number of elements of V_c or by the minimum number of elements of V_c needed to meet a certain accuracy requirement. We preferred the latter since we want to describe shape features with a pre-set accuracy and with a minimum number of vertices.

The degree of accuracy is measured by a function $dev(i,j)$ which is the maximum distance of all vertices v_k between two vertices v_i and v_j and a line through v_i and v_j . The accuracy of an approximation V_c is satisfactory if $dev(i,j)$ is less than some maximum deviation $maxdev$ for all lines $\langle v_i, v_j \rangle$ of V_c . The search for an optimal subset V_c of V is realized as search for a maximum cost path in a graph whose nodes are vertices of V and whose arcs are straight line segments between nodes. (In the following we are doubling the set of vertices in V such

that $v_{n+i}=v_i$ for $i=1, \dots, n$. That simplifies our explanations since the wrap-around effect at the two vertices v_n and v_1 has not to be taken into account.)

For arcs representing lines $\langle v_i, v_j \rangle$ with $0 < i, j < n+1$ we define the cost function

$$\text{cost}(i, j) = \begin{array}{ll} j-i-1 & , \text{ if } \text{dev}(i, j) < \text{maxdev} \\ 0 & , \text{ otherwise.} \end{array}$$

Using the cost function above we apply the algorithm in figure 1 to search for a maximum cost path starting at vertex v_1 . The result is a subset V_{n+1} of V with the smallest number of vertices of all subsets which include the vertex v_1 and whose accuracy is satisfactory. (The accuracy requirement is met, since the cost of arcs is set to 0, if the deviation of approximated vertex positions exceeds *maxdev*.)

```

begin
  node=1;
  pathcost1=0;
  node=node+1;
  while node<n do
    begin
      pathcostnode=cost(1, node);
      for i=2 until node-1 do
        begin
          if pathcosti+cost(i, node)>pathcostnode then
            begin
              pathcostnode=pathcosti+cost(i, node);
              Vnode=Vi U {v1};
            end;
          end;
        end;
      end;
    end.

```

figure 1: Optimal contour approximation

Since the solution is only optimal for contours containing the vertex v_1 , the procedure has to be repeated $n-1$ times using the vertices $\{v_2, \dots, v_n\}$ of V as start nodes. The maximum cost path of all these runs corresponds to a contour with the minimum number of vertices satisfying our criterion of accuracy. That criterion, of course, can be replaced by others to achieve different results (e.g., by the area under the approximating polygon line to allow for noise corrections[1]).

The computation time of the algorithm increases cubically with the number of vertices in V . Since a boundary in a typical CT scan may have more than 4000 vertices, computation times can be unacceptably high. Therefore we did not apply the method for contour approximation, but to test the quality of faster but sub-optimal methods.

Two heuristic approaches

There are several ways to do a faster but sub-optimal contour generation. Algorithms of that kind can be subdivided into two classes. The first class includes algorithms which, starting at an arbitrarily selected initial vertex, extend lines until the accuracy of the line approximation is no longer satisfactory [8],[10],[11]. We will name this kind of algorithm Continued-Line-Extension(CLE)-algorithm. A basic algorithm can be implemented with quadratically increasing computation costs (see figure 2) though faster realizations are known[8]. The initial vertex v_{start} in that algorithm is the vertex with maximum x -value since a vertex at a local maximum of the boundary is a likely candidate for an approximation.

```

begin
   $V_c = \{v_{start}\};$ 
   $v_{actual} = v_{start+1};$ 
  while  $v_{actual}$  not equal  $v_{start+n}$  do
    begin
      if  $dev(start, actual) > maxdev$  then
        begin
           $V_c = V_c \cup \{v_{actual-1}\};$ 
           $v_{start} = v_{max};$ 
          ( $v_{max}$  being vertex with maximum deviation)
        end;
      else
        begin
           $v_{actual} = v_{actual+1};$ 
        end;
      end;
    end;
  end.

```

figure 2: Contour approximation by continued line extension.

Another class of algorithms uses a different approach. It starts with two vertices $\{v_{c(1)}, v_{c(2)}\}$ which form two initial line segments $\langle v_{c(1)}, v_{c(2)} \rangle$ and $\langle v_{c(2)}, v_{c(1)} \rangle$. They are subject to an iterative

subdivision process where those line segments in V_c are subdivided which do not satisfy the accuracy criterion. The subdivision takes place at the vertex of maximum deviation from the segment. An algorithm of that kind was suggested by [6].

```

begin
   $V_c = \{v_{c(1)}, v_{c(2)}\};$ 
  subdivide = on;
  while subdivide is on do
    begin
      subdivide = off;
      for each segment  $\langle v_{c(i)}, v_{c(i+1)} \rangle$  do
        begin
          if subdiv( $\langle v_{c(i)}, v_{c(i+1)} \rangle$ ) is necessary do
            begin
              find  $v_{div}$  of max. distance to  $\langle v_{c(i)}, v_{c(i+1)} \rangle$ ;
               $V_c = V_c \cup \{v_{div}\};$ 
              if dev( $c(i), div$ ) > maxdev then
                begin
                  subdiv( $\langle c(i), div \rangle$ ) = necessary;
                  subdivide = on;
                end;
              if dev( $div, c(i+1)$ ) > maxdev then
                begin
                  subdiv( $\langle div, c(i+1) \rangle$ ) = necessary;
                  subdivide = on;
                end;
            end;
          for each triple  $(c(i-1), c(i), c(i+1))$  do
            begin
              if dev( $c(i-1), c(i+1)$ ) < maxdev then
                begin
                   $V_c = V_c \setminus \{v_{c(i)}\};$ 
                end;
            end;
          end;
        end;
      end;
    end.

```

figure 3: Contour approximation by subsequent subdivision.

After subdivision adjacent segments may be merged to a single segment, if that segment still meets the accuracy requirements[5]. We name this algorithm Subsequent-SubDivision(SSD)-algorithm. The

algorithm also exhibits quadratically increasing computation costs (see figure 3).

The two initial vertices of the SSD-algorithm are those which form a line with minimal angular deviation from the first principal axis of all vertices. (The first principal axis $\langle fpa \rangle$ of a set of vertices is an axis with minimal mean square distance to all vertices[3].) However, to exclude initial lines which are too short we decided to add a weighting factor which is proportional to the length of a line segment:

$$priority(\langle v_i, v_j \rangle) = length(\langle v_i, v_j \rangle) / angle(\langle v_i, v_j \rangle, \langle fpa \rangle)$$

The vertices of the line with the highest priority score are chosen to be the initial vertices of V_c .

Results

The two heuristic approaches were compared with the optimal contour approximation method by testing the algorithms on binary scenes of PET scans of the head. The accuracy was set such that all approaches reduced the number of boundary vertices by the order of a magnitude. The optimal method, however, resulted in 30% to 80% less vertices than the two heuristic approaches. Of the heuristic methods the SSD-algorithm had a better performance than the CLE-algorithm. On average the SSD-algorithm needed about 30% fewer vertices than the CLE-algorithm. The reason for this is perhaps the possibility of the SSD-algorithm to alter the contour after subdivision by joining adjacent line segments whereas the CLE-algorithm does not allow the removal of a vertex once it is selected for the contour approximation.

Conclusions

In this paper we have demonstrated a new algorithm for an optimal contour approximation. We used the method to test two heuristic approaches. We found that the method of subsequent subdivision was superior to the method of continued line extension though both algorithms did not achieve optimality.

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Practical Segmentation of MRI Data

J. Ylä-Jääski, T. Veijonen and H. Ahonen

Graphic Arts Laboratory, Technical Research Centre
of Finland, Espoo, FINLAND

R. Repo

Nokia Data Systems Corporation, Helsinki, FINLAND

Abstract

Segmentation of meaningful anatomical objects from raw intensity data is a fundamental operation in computer assisted analysis of multidimensional medical images. Due to high demands for the reliability of the segmentation fully automatic segmentation procedures applicable to MRI images are unlikely to be accepted in a clinical practice. We present an implementation of a segmentation concept which is based on 2D and 3D edge detection algorithms. The edge elements which have been detected automatically are complemented by efficient interactive tools. These enable the user to construct the final objects while incorporating his expert knowledge in the interpretation. The segmentation tools combined with efficient techniques for visualization and quantitative analysis constitute the basic modules in an image processing workstation for clinical applications and utilizing volume data.

1. Introduction

Recent advances in magnetic resonance imaging (MRI) with respect to image quality and data acquisition speed have brought the use of MRI volume data into routine clinical use. In addition to the development of data acquisition also efficient tools for the analysis and visualization of volume data are required for an optimal exploitation of the information. During the last few years a number of 3D visualization techniques have been developed. They have demonstrated their usefulness in various medical applications such as in diagnosis and in planning and monitoring of therapies [1].

The successful development and implementation of fast and efficient tools for volume visualization should not obscure the fact that automating the

segmentation of MRI volume data has remained a largely unsolved problem. Promising results for MRI data have been obtained by extending standard edge detection algorithms into 3D and applying them to volume data [2-3] or through the use of multispectral classification techniques [4]. However, in practice the user frequently has to draw the object contours manually on each slice of the data volume to obtain a clinically valid and accurate result.

Segmentation of meaningful objects from raw volume data is an essential and integral step towards computer assisted analysis and efficient visualization of multidimensional medical data. Due to the high demands for accuracy and reliability of the segmentation in medical applications fully automatic procedures are unlikely to be accepted in a clinical practice. Thus successful practical segmentation techniques must be able to combine automatic algorithms with efficient and user-friendly interactive methods.

In this study a practical segmentation scheme based on standard edge detection algorithms is presented. Edge elements which have been determined automatically are interactively modified and grouped into closed object contours. This interactive stage is based on minimizing the energy of a spline curve by taking into account both external constraint forces and image forces [5]. The external constraints are imposed by the user to guide the contour to take a desired route and the image forces are tuned to pull the contour towards specific image features such as edges or lines.

The development of practical segmentation techniques for MRI images forms part of a research effort which aims at developing a workstation for 3D medical image processing workstation based on standard computer hardware. The basic software components of the system consist of segmentation, visualization and analysis techniques for volume data together with the necessary administrative tasks. The software will be tailored to suit specific clinical fields by application specific modules.

2. Segmentation of multidimensional data

2.1 Segmentation scheme

Medical data typically represents an image interpretation task for which the correct interpretation requires very high level expert knowledge. The

interpretation may even differ depending on the actual application of the results. Segmentation which is only based on low level techniques clearly cannot lead to a reliable result.

The central feature of the segmentation scheme developed in this study is that in addition to any automatic procedures one has to provide the user with efficient interactive tools to manipulate the output of automatic algorithms. These tools allow the user to direct the segmentation result toward the desired solution.

2.2 Edge detection

The interactive tools have to be supported by automatic procedures which provide a starting point for the refinement of the result. Edge detection has been chosen to form the basis of the initial automatic stage of the segmentation scheme.

For edge detection, we currently use either the Canny operator [6] or one of two approximations of the Marr-Hildreth operator [7] (Difference of Gaussians or Laplace of Gaussian). All the currently used edge detection methods have been implemented both as 2D and 3D operators. During the segmentation procedure volume data can be considered as a set of 2D slices or a true 3D volume. The 2D slices for the segmentation can naturally be selected orthogonal to any of the three main axes of the volume. For a 3D application of the operators the data has to pre-interpolated into cubic voxels.

A control over the desired image details is provided by the half width σ of the Gaussian function which is contained in the operators. The Difference of Gaussians operator contains two Gaussian functions; the ratio of the width values between the two Gaussians remains constant. For large values of σ noise is efficiently smoothed out, but also important details and accuracy in the edge locations may be lost whereas the use of small σ results in good reproduction of details but also in an increased noise level. The actual width σ to be used is currently determined experimentally for each case separately.

Besides the resolution level the user can control the output of the edge detection by a selection based on the edge strength. This is carried out interactively on the screen by modifying the threshold operating on the output of the edge detection operator. At this stage the user also selects

those edge elements which are to build up a basis for the successive refinement of the object contours.

2.3 Interactive object refinement

The automatic edge detection procedure is complemented by techniques relying on interactive operation to obtain a reliable segmentation result with a minimum of user interaction. The user can pick up edge elements from different resolution levels and combine edge elements representing different levels of edge strength to form initial components of object contours. These initial components can be declared fixed or they can be allowed variable subject to similar procedures that are applied on the edge linking into closed object contours. The object refinement stage can even be carried out completely from scratch without a prior edge detection step.

The edge elements are modified and linked together using an approach based on minimizing an energy function [5]. An energy function is determined for a line between two points consisting of image, line, and external forces and a local minimum for this function is determined iteratively. The process is initiated at a straight line between the two points or a result from the edge detection process.

Image forces which are contained in the energy function currently can be tuned to follow edges, ridges, or valleys in the image. The line forces tend to smoothen the line avoiding sharp corners. Through the insertion of external forces the user can additionally pull the line towards a selected location or push it away from another one thus directing the energy function from one local minimum to another desired one. The relative weights for the components of the total energy function can be modified interactively thus providing the user with powerful tools for semi-automatic segmentation.

2.4 Postprocessing

All the 3D visualization techniques that we currently are using are based on direct surface reconstruction from voxels. The image data is stored as an array of voxels throughout. The segmentation results occupy either predefined bit planes of each voxel or build a voxel array of their own. In order to obtain classified voxels the object contours on each slice are filled

using standard graphics algorithms followed by a 3D connected component labelling procedure [3] to finally yield the 3D object description in the voxel format.

3. Implementation

The segmentation algorithms and the user interface have been developed using Symbolics workstations and Common Lisp as the programming language. The algorithms form an integral part of a menu-driven image processing software package developed at Technical Research Centre of Finland, Graphic Arts Laboratory. The main applications of the package are multidimensional medical images and binary images such as maps and technical documents.

The software is currently being integrated into the UNIX operating system using the C-programming language under the X-Windows environment as part of a software development project aiming at a workstation for multidimensional medical image analysis. All visualization algorithms are voxel based utilizing the so-called prebuffer algorithm [3] for fast surface reconstruction.

4. Conclusion

A segmentation scheme for medical volume data has been presented. The scheme incorporates low level image processing techniques in the form of edge detection filters. The edge detection result is complemented with high level expert knowledge through an interactive procedure using the automatically detected edges as input to refine the final object contours. The segmentation techniques have been integrated in a voxel based 3D visualization package.

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Finding Parallel Structures in Medical Images

S. T. Rake

IBM UK Scientific Centre, Winchester, ENGLAND

Medical images, like images from other domains such as manufactured objects and natural scenes, are full of structures, groups of features with some form of spatial regularity. In many domains parallel edged structures are of particular interest and the automatic extraction of those structures has been addressed by many researchers.

For instance, there has been considerable work in identifying arteries by *tracking* where an operator specifies a location in the image that is inside an artery and an initial tracking direction (1,2), or by an analysis of small areas of the image which may indicate the presence of an artery. This and other evidence is combined to produce possible artery traces (3,4). These processes are invariably domain dependent, looking only for arteries, with some form of encapsulated domain knowledge which makes them inappropriate for other tasks. This is essentially a local *Pattern Recognition* approach.

However, if a more global analysis is performed using ideas developed from *Computer Vision*, then it is possible that processes can be developed which will identify features from a wide range of domains with no operator intervention. The concept of interest is that of a *Semantic Pre-cursor*(5) in which a structure is identified before it is named as a particular object. In this paper parallel edged structures are of particular interest.

There are many types of medical image in which parallel edged structures appear. One obvious case is an X-ray angiogram, but there are other modalities in which a parallel edged structure is a useful landmark in locating the feature of interest. This paper describes a set of processes which will identify parallel structures over a wide range of modalities, three of which are shown in the results. In order to emphasise the semantic free nature of the identified structure they are called *Ribbons*. The processes are edged based, starting with a local assessment of the presence of an edge and building up larger structures until all the ribbon structures in the image have been identified. A *ribbon model* aids in the resolution of ambiguous data. A full description of the processes can be found in (7).

The Ribbon Finding Processes

Edge Detection

The first process is to identify edge points that occur in the image. At this stage no attempt is made to assess their usefulness as edges of ribbons. The CANNY operator (6) has been found to give good quality edge data in a number of different domains since it gives a good signal to noise ratio at an edge. The output of the process is a list of points that have been identified as edge points. Each item in the list has the X and Y coordinate of the edge point to sub-pixel accuracy, the orientation of the edge point from 0° to 360° and the strength of the edge point which is a measure of the contrast across the edge. The edge points are thresholded to eliminate those that are below a certain strength and thus likely to be of less interest than points above the threshold.

The next process is to group the edge points into larger entities. Since we perceive adjacent edge points in the image as *connected* and a set of connected edge points as one perceptual group, an *edge*, the larger entities will be an *edge list*. Each point in an edge list is classified as a *terminator* (the end of an edge list), a *line point* (a point inside an edge list) or a *junction* (coincident terminators from two or more edge lists).

Finding all Ribbons

Having identified continuity *along* the edge segment and grouping the relevant edge points into edge lists, we are now in a position to look for ribbons. A ribbon is defined by two edge lists in which there are points which satisfy distance and orientation constraints. One edge point is part of a ribbon edge if there is a point in a second edge that is close, within the constraints. The corresponding points define the *Line Generators* of the ribbon and an ordered list of Line Generators defines a ribbon.

Self-parallel edges are single edges which 'double back' on themselves to produce close, parallel, edge points of opposite orientation. This type of edge is surprisingly common, and occurs most often when there is good contrast between the ribbon and the surrounding areas of the image.

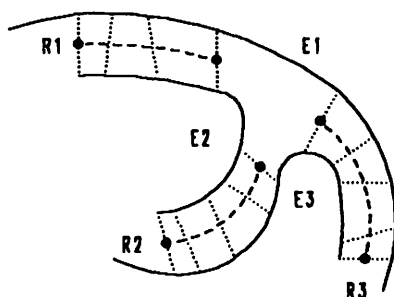


Figure 1. Edges generate ribbons: Edges E1, E2 and E3 generate ribbons R1, R2 and R3. The dotted lines are the Line Generators and the dashed lines are the ribbon centre lines.

Removing the Ambiguities

Since the search for ribbons is exhaustive it is possible for two ribbons to be identified which use the same part of the same edge. The use of the edge is said to be *ambiguous*. There are two broad categories of ambiguity, as shown in Figure 2.

Ambiguities are resolved by deleting data. *Wide Ribbon Deletion* is used to delete a whole ribbon. If the ambiguity is of the type (A) in Figure 2, deleting the wider ribbon R2 will remove the ambiguity. *Common Point Deletion* is used to 'crode' the ends of ribbons by deleting one Line Generator at a time until the ambiguity is removed. In Figure 2 (B), the deletion of the individual Line Generators at the point of overlap will remove the ambiguity and still retain most of the data in R1 and R2.

Finding the Junctions

After the ambiguities between ribbons have been removed, the remaining ribbons will consist of a number of disconnected ribbon pieces. If the ends of the ribbons are close (to some criterion) then, in some domains, it may be appropriate to try to *join* the broken ribbons. For instance, in cardiac angiograms it may be reasonable to make an initial assumption that the ribbon structures will be continuous and an attempt to repair the breaks in some way is accept-

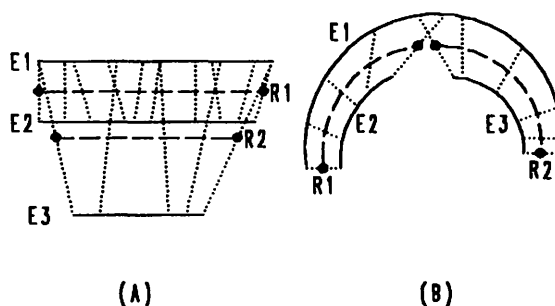


Figure 2. The Categories of Ambiguity:

- (A) Wide ribbons. The ambiguity is resolved by completely deleting the wider ribbon, R2.
- (B) Overlapping ribbons. The ambiguity is resolved by deleting the Line Generators causing the ambiguity.

able. There are domains in which it is important to identify the more complex structures where three or more ribbons meet, a *junction*. For instance, in angiograms, the point at which an artery divides (a bifurcation) is of considerable interest and the bifurcation can appear in the image as a junction of three ribbons. The processes repair the local breaks and identify the junctions, using evidence existing in the image and already extracted by an earlier process.

One piece of evidence is the *proximity* of the ends of the ribbons, and the other is *continuity* of an edge between two ribbons. If continuity is combined with proximity, the inference of a ribbon join or junction can be made.

Results

The processes described above were run over three types of medical images. Figure 3 is a digitised radiograph of one of the views of one stage of the heart beat cycle. It shows the cardiac arteries after the injection of the radio opaque material. Figure 4 is an MRI image and is a horizontal slice located just above the ears. The structure of interest is the bright ribbon of the scalp. Figure 5 is of a preparation, viewed through a microscope, of a cross-section of muscle fibre. The structures of interest are the bright ribbons between the darker fibres. All the images are 256 pixels square.

There is not sufficient space to show the results of the processes at each stage. However, the figures below show a representation of the extracted ribbon data, after ribbon extension and junction identification.

The only tuning of the processes is by two sets of global parameters, one to control the thresholding of the edge points, the other to control the dimensions of the structure being investigated.

In general, where a parallel structure exists in the image, a ribbon has been identified. Inspection of the edge lists produced by the edge detector shows that where there is no ribbon, there is insufficient edge data to infer a ribbon. The parallel structures are incomplete in some cases. This is to be expected - no process will produce perfect results in the type of images being processed here. In some cases, parallel structures have been identified which are not caused by the features of interest in the image. This is also to be expected. The processes are identifying 'semantic pre-cursor' structures which will require a later understanding process to separate out the 'real' objects from the 'artefacts'. What is especially interesting is that very few artefacts have been identified.

The results of the intermediate stages are described in the full report on this work (7), together with performance figures and implementation details.

Conclusions

The results show that the methods described here can produce good quality descriptions of parallel edged structures in images from a number of different domains. The processes are identifying 'semantic precursors' of objects, such as arteries in the HEART image, the scalp in the HEAD image and the boundaries between the fibres in the MUSCLE image. The processes have no knowledge of arteries, heads or muscle fibre.

The accumulation of evidence for the existence of a ribbon and the use of a ribbon model (defining how a ribbon can appear in an image), results in the ribbon structures being accurately identified and located.

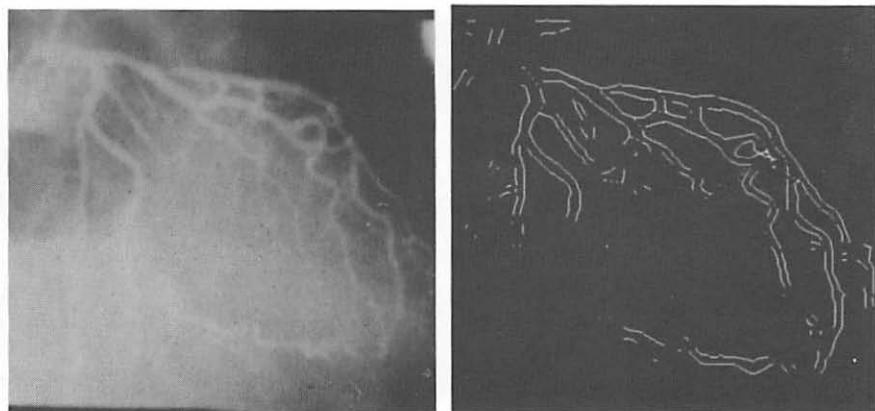


Figure 3. HEART: The original image is an X-ray cardiac angiogram after the injection of radio opaque dye. The identified ribbons are shown on the right.

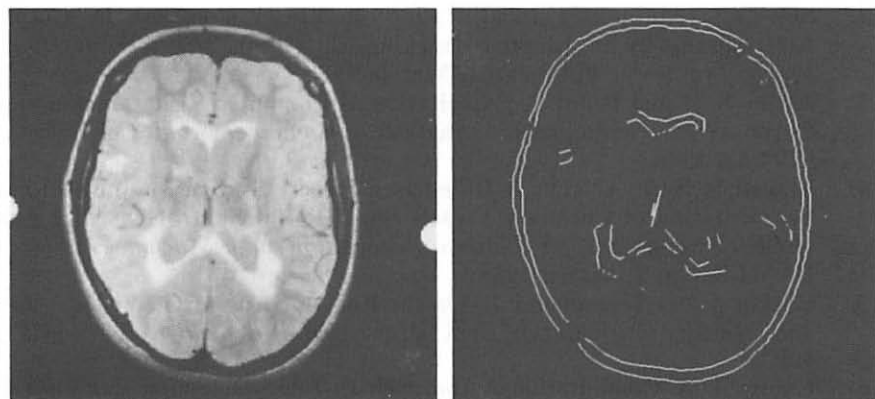


Figure 4. HEAD: The original image is an MRI image. The identified ribbons are shown on the right.

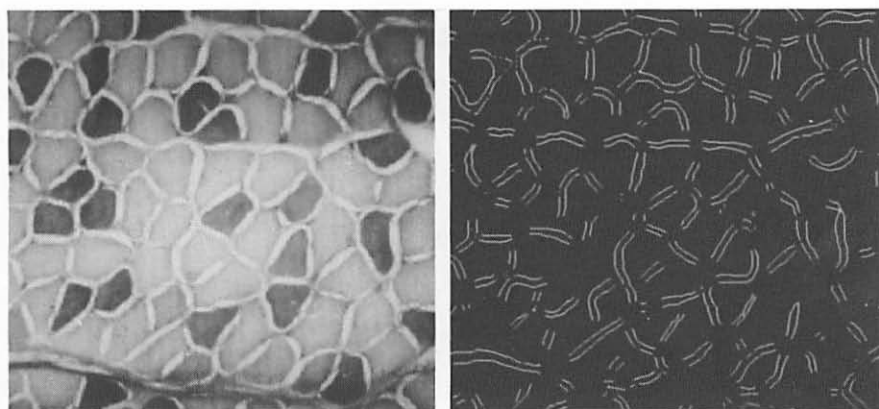


Figure 5. MUSCLE: The original image is a cross-section of muscle fibre. The identified ribbons are shown on the right.

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Teaching and Research

General Session

Decision Support in Diagnostic Radiology

Henry A. Swett

Department of Diagnostic Radiology, Yale University
School of Medicine, New Haven, CT

The rapid evolution of computer-based technologies in diagnostic radiology is creating a digital environment that is bringing unprecedented power to radiologists. Clinical information systems and image management and communication systems can deliver a wealth of clinical and image information. New systems are being developed that focus medical knowledge on this clinical and image information. This added dimension of automatic access to highly specific knowledge offers the potential for radiologists to exhibit expertise far beyond currently recognized human limitations.

Decision making in diagnostic radiology occurs at many levels. Our primary focus is on diagnosis. To make a diagnosis, we must understand the implications of the patient's clinical history. We often must help the patient's physician choose the most appropriate imaging examination or examinations and then make sure that the studies that are performed maximize information yield. Our greatest intellectual challenge begins when the images are before us. What abnormalities can we identify and what do they mean in the clinical context in which they are presented to us? Have we seen all there is to see and have we accurately characterized what we have seen? Have we not only understood the significance of each individual finding, but have we put it all together correctly? Ideally, our analysis of these clinical and radiographic findings lead to a specific diagnosis. Often, however, we must settle for a list of possible diagnoses. Then we must progressively narrow this differential diagnosis list - first by applying knowledge or "expertise" and then by recommending additional imaging and sometimes clinical workup.

How can computers help us make decisions in diagnostic radiology?

Computers can either make decisions directly or can act as a 'knowledge servant' that helps us make decisions more effectively. For nearly two decades, investigators have been interested in *computer diagnosis*¹. Computer diagnosis systems often directly process clinical data and attempt to make a diagnosis by simulating human thought processes. This may be effective in certain clinical settings where diagnoses can be reduced to well defined algorithms and where clear cut, often quantitative, data are available. Despite some impressive successes in the laboratory², few of these

systems are used clinically. There have been several interesting systems that have been built in diagnostic radiology that deal with specific problems such as bone tumor diagnosis, and the evaluation of the arthritides^{3,4,5}.

Decisions in radiology often do not lend themselves to this approach, however, because of the often very subjective nature of image interpretation. As a result, the computer may be more effective if it can support our own thought processes, rather than replace them. One way to do this is to cast the computer in the role of a 'knowledge servant' whose job it is to present us with knowledge that can enable us to make decisions more effectively. This would provide a very complementary relationship between us and computers. Humans, after all, have poor memories, and process information slowly (approximately 50 bits per second). We also only think about one thing at a time (we are serial processors). We excel, however, at making intuitive judgements about things that we do remember. Computers, on the other hand, have almost unlimited memories and can process and retrieve information at very high speed. It is much more difficult to get computers to make the kind of intuitive judgements that we make easily. Therefore, it makes good sense to combine these different human and computer strengths so that the combination is more powerful than either separately. One of the ways that computers can serve us in medicine is to *filter* information for us. Since we process information so slowly, we can't possibly keep up with all of the important information that is available. Information from the patient's clinical record, books, journals - we are overwhelmed. It is daunting to realize that new knowledge is created so rapidly in medicine, that the entire body of medical knowledge doubles every five years. The result is that it is becoming almost impossible to practice state-of-the-art radiology, even if we only practice a subspecialty. Fortunately, the computer can help us stem this flood of knowledge by filtering it for us. It can evaluate the clinical data that is known about our patients as well as the observations that we extract from their images and deliver carefully selected information to us in a way that helps us understand their implications.

We have been exploring many of these issues at Yale through the Image/Icon family of prototype decision support systems^{6,7}. These artificial intelligence-based systems seek to 'understand' the issues the radiologist is dealing with by directly evaluating his or her case description together with the patient's clinical history. These systems present selected or 'filtered' information based on these findings in two different ways. First, the system produces an English prose discussion of the significance of the issues raised by the case. Second, the system retrieves and displays images from an image database that are likely to help strengthen the radiologists working diagnosis, or cause him or her to consider another diagnosis. Several systems have been developed to bring computer-based advice to bear on the process of selecting diagnostic imaging procedures^{8,9,10}.

Direct computer interaction with images may play an increasingly important decision support role in the future. This may involve standard image processing methods

to improve contrast resolution, manipulate spatial frequency, energy subtraction, etc. In special circumstances, some computer systems have begun to be able to extract 'information' directly from images. Interesting research has been done in computer identification of lung nodules¹¹, breast masses¹², breast calcifications¹³, and in the automatic identification of such anatomic structures as cardiac chambers¹⁴. It is important to emphasize that widespread automatic image interpretation by computer is not likely to occur in the foreseeable future.

The Intelligent Radiologic Workstation

Image management systems, clinical data management systems and knowledge-based decision support systems have been evolving separately. The sophistication of the digital environment that is becoming commonplace in diagnostic radiology offers the opportunity to bring these separate technologies together in the form of an intelligent radiologic workstation. This union will produce a device of unprecedented power that will not only display and process images, but will provide a portal to vast libraries of information. It will filter this information for us and focus it on our immediate clinical problems. It will do this in real time - at the moment of truth - when we are making clinical decisions. The result will be a tool that will significantly extend our intellectual powers.

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The Radiographic Feature, Test Case Databases and the Application of Informatics to Radiology

Kenneth Levin

Division of Nuclear Medicine, Georgetown University Hospital,
Washington, DC

Abstract

This paper discusses the applications of informatics to Radiology. Informatics is the study or use of information and system sciences in association with computers (1). In this paper, I will discuss the radiographic decision making process, how this can be modeled with advice programs, difficulties in writing and verifying an advice program, and potential benefits of this research.

Introduction

Radiology is an excellent area for applications of Artificial Intelligence (AI) research because much of the reasoning process of radiologists is rule-based and many AI programs use rule based programming systems. Radiologists will frequently use rules such as:

 If the heart is enlarged, and
 if there are Kerly B lines, and
 if there is alveolar edema,
Then, there is a high likelihood that the
 patient has congestive heart failure.

It is felt that this research will lead to improving the rules that radiologists use to link radiographic features on a radiograph to a diagnosis, develop computerized representation of radiographic knowledge, help standardize radiographic terminology, ease report generation from a radiographic diagnostic workstation,

improve the user interface of a diagnostic radiology workstation, assist with teaching radiographic concepts to radiologists and testing performance of future radiologists.

Radiographic Decision Making Model

The principle task of the radiologist is to analyze images and provide a diagnosis. Through training, the radiologist has learned to examine an x-ray and integrate the shadows present on the image to give a diagnosis. If asked to explain a diagnosis, the radiologist will describe the radiographic features that are present on the image and how he reasoned about these features to give the diagnosis. He will also take into account clinical details of the case.

From the above discussion, it follows that the radiologic decision making process can be modeled by a two step process. In the first step, the radiologist analyzes the images and either implicitly or explicitly defines a set of features. The next step is to reason about the presence and absence of the features on the film and incorporate these into a diagnosis. I have chosen to use the term radiographic features in this discussion. This process was first described by Blessner and Ozonoff in 1972 (2). They described a three-step model, but the first step consisted of image formation. Others have discussed the distinction between features and reasoning (3-5).

The most common reaction to a discussion of AI, radiographic features, rules, etc., by radiologists is: "I don't use rules, features, or any of that non-sense. I look at a film and I 'know' the diagnosis." However, this misses the point! Yes, a trained radiologist "just knows" the answer, but during training, he or she learns what the radiographic features are and how to reason about them. It is a sign of being a trained radiologist that this two-step process has been transformed into a one-step

process. Psychologists call this process chunking.

One categorization of artificial intelligence programs in Radiology is that there are programs that attempt to categorize the "signal", i.e., the image data, and whose output is a list of radiographic features. The second category of program uses this set of features as input and produces advice (such as a diagnosis) as output. A radiologist performs both of these functions. I have chosen the terms front-end program (FEP) and advice program (AP) respectively to describe these two functions. Advice programs could be expert systems, neural nets, or statistical programs. These can be submodules of a larger program.

When building a machine that is capable of radiographic image interpretation, it will have to "learn" by being programed with an internal representation of these same radiographic features, rules. At the end of the development process, a system that has FEP and AP capabilities should, likewise, be able to "examine" the image and "just know" what diagnoses may be present; that rules, frames, confidence factors, fuzzy logic, etc., may have been used in the process is immaterial.

It has been shown that perception of radiographic features has significant inter- and intra-observer variability (6-9). An implication of this is that it is difficult to validate the accuracy of an advice program. To obtain a set of cases which has "known" findings on the images and proven pathology is difficult (10-11). This is a problem only when one tries to identify the radiographic features present on each study. For instance, when the system under observation consists of both a FEP and an AP (whether this system is human or computerized), then the output of the system is a diagnosis which can be compared with some external standard of "truth". When trying to identify the radiographic features of a set of cases (i.e., when trying to analyze the data that is

exchanged between a FEP and an AP), there is no objective way to determine which features are present because these are the perceptions of individuals. A method has been proposed for deriving a test case features database by having multiple observers interpret the test cases and deriving a set of "consensus" features (12).

Another problem with identification of radiographic features is that there are subtle differences in the terminology used by radiologists. This leads to variability in describing radiographic features. The havoc that this can cause when using advice programs is described by Piraino, et.al., (13) and Bramble (14) (Garbage In, Garbage Out).

Constructing an Advice System

When one attempts to construct an advice system, there are several prerequisites. The first is the availability of an adequate number of cases with known diagnoses and with a reasonable number of difficult and subtle cases of the diagnosis between which one is attempting to differentiate.

After acquiring a suitable number of cases, the next step is to determine which radiographic features are necessary components of the domain and to determine which programming technique will be used to form the advice part of the system. This step can be performed by rule-based systems in which case the rules will have to be determined. Either a textbook or an expert can be used as the knowledge source. Traditionally, interrogation of experts has been used for the knowledge acquisition process. With neural nets and statistical programs, the rules do not have to be developed because the relationships are derived numerically.

After having developed the advice program, the expert system should be validated. In order to validate computer programs, known input must be provided to see if the system will produce the correct output. I have already described

the problems inherent in determining the "correct" radiographic findings on a set of radiographs. After developing the test case feature database, the expert system can be validated and if necessary the rule base can be refined until performance is satisfactory.

Uses of Advice Systems in Radiology

At this point let us assume that one has collected an adequate sample of test cases. A database of the correct features on these cases has been assembled by consensus readings, and an advice program has been developed and validated by using the test case feature database. I am proposing several uses of advice programs in radiographic research.

The effort of developing the test case feature database will be of value in and of itself. The inter- and intra-observer variability will be defined for this group of cases and for this diagnostic domain. If there is a particular feature which is perceived with very little agreement among radiologists, then the use of this feature in making diagnoses should be questioned. Conversely, those features agreed upon with a high frequency can be used with high confidence. The effect of a systematic search on diagnostic accuracy can also be evaluated.

If the advice system is developed using expert systems methodology, then the refined rules can be reverse translated into English and used as an improved codeification for the interpretation of this category of examinations. This process of using rule-based expert systems to improve the rules used by experts has been called knowledge refinement (Michie, D. Personal Communication).

The problems of non-standardized radiographic terminology have been discussed previously in this paper. The use of computerized advice programs has pointed out a problem with noise which is inherent in the English language

descriptions that humans deal with fairly easily. However, in this decade of increasing computerization, standardization of terminology should be performed. Or if standardization cannot be implemented, then thesauruses of equivalent terms should be developed for human and computer use. (This might come to pass from the Unified Medical Language Project of the National Library of Medicine.) With computerized advice programs, definitions of features including illustrations should be available on-line.

Advice programs can be used to help teach and test radiologists. For instance, the benefits of various teaching methodologies may be compared in the following fashion: A group of naive students is shown a set of cases and are asked to interpret the cases by describing the findings which are present on each film and the diagnosis. This initial group is sub-divided and each sub-group is given alternative methods of instruction of how to interpret this category of exams. Subsequently, a second set of test cases is shown to the sub-groups. The ability of the individual groups both to perceive the radiographic findings and to make the correct interpretation following the different means of instruction can be objectively assessed in this manner using advice program technology.

These systems can be used to assess the skill of practitioners either during initial certification or re-certification. The candidate can interact with the advice program by describing the radiographic features present and give his/her diagnosis. Perception of the individual features can then be compared with the test case feature database to see if they match the performance of a suitable percentage of peers. In addition, ability to make the correct diagnosis will be recorded by the system as well. Therefore, one can compare both the perception of individual findings and the differential diagnosis. This may ease the burden of oral and/or re-certification

examinations which the profession has to confront in the future.

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E.T. NET: A Free Computer Conferencing System Dedicated to Applications of Computers in Health Sciences Education and Radiology

Michael D'Alessandro

Department of Diagnostic Radiology, University of Iowa Hospitals and Clinics, Iowa City, IA

Robert O. Bollinger

Department of Pediatrics, Wayne State University, Detroit, MI

Michael J. Ackerman

The Lister Hill National Center for Biomedical Communications, National Library of Medicine, Bethesda, MD

Description

The E.T.Net (Educational Technology Network) is a one year old, free, easy to use, 24 hour accessible, online computer conferencing system organized by the National Library of Medicine which is accessible via a local phone call to the Telenet (Sprintnet) computer network. It is dedicated to helping bring together, in a single continuously running electronic forum, developers and users of computer applications in health sciences education and radiology.

E.T.Net's advanced computer conferencing software allows individuals who are geographically and temporally separated to unite electronically in order to participate, at any convenient time for them, in interactive discussions on applications of computers in health sciences education and radiology. Computer conferencing software is a still relatively unknown form of computer software that facilitates a structured and organized exchange of online information and ideas, and is a distinct improvement over the more widely known computer bulletin board software that facilitates an unstructured and unorganized exchange of online information and ideas. A computer conferencing system such as E.T.Net provides the valuable service of allowing health sciences professionals to conveniently remain in regular contact with colleagues on issues when they are not physically together at face to face conferences.

E.T. Net is organized hierarchically, and consists of several computer **conferences**, each encompassing a broad but related subject area of potential discussion. Each conference is further subdivided into **items**, with each item serving as a starting point for a discussion on a topic. Discussion is carried out by participants adding **responses** directly to the appropriate item. Each conference has an index of all the items within it. Each time one logs onto E.T. Net, for each conference they belong to, they are shown the new responses to old items and the new items that have been added in the interval, and they are given the opportunity to add their own responses to preexisting items and to add their own new items.

E.T. Net was conceived to facilitate communications between health sciences professionals utilizing computers in health sciences education and therefore the majority of the conferences and hence discussions on E.T. Net deal with applications of computers in health sciences education and include: integration of computers into health sciences educational programs in the basic and clinical sciences, development of new and evaluations of existing health sciences educational software, uses of videodisc and CD-ROM hardware technologies in health sciences education, uses of hypermedia and artificial intelligence software technologies in health sciences education, computing in health sciences libraries, training and careers in medical informatics, and the ultimate goal of easily organizing and disseminating medical information.

In addition, there is a conference on E.T.Net, entitled "digital_images," dedicated to applications of computers in radiologic practice and education. Topics of discussion include but

are not limited to: radiologic education via hypermedia and computer aided instruction systems, digital radiography and picture archiving and communication systems (PACS), image processing and three dimensional image reconstruction techniques, teleradiology, radiology information systems (RIS), uses of artificial intelligence in radiology, and how computers can aid radiological research.

E.T.Net uses the Caucus computer conferencing software (1) running on a 80386 based microcomputer using the Xenix operating system. This microcomputer is located in the National Library of Medicine's Lister Hill National Center for Biomedical Communications in Bethesda, Maryland and is directly connected to the Telenet packet switching network. A user connects to E.T.Net by placing a phone call to their nearest Telenet node using a personal computer and a modem and the Telenet node then connects them to E.T.Net. E.T.Net is currently configured to allow its use by up to four people simultaneously, and if necessary this may be expanded to eight simultaneous users in the future. As part of its mission of disseminating medical information to health science professionals, the National Library of Medicine covers the cost of running E.T. Net as well as the Telenet charges of E.T.Net users.

A startup information packet is available directly from the Educational Technology Branch of the Lister Hill National Center for Biomedical Communications at the National Library of Medicine (2) or alternatively, one may follow the instructions in the Appendix below to logon to E.T.Net for the first time. All one needs to access E.T. Net is a personal computer with communications software and a modem.

Participation on E.T.Net is open to all health sciences professionals and students.

References

1. Camber-Roth
243 Hoosick Street
Troy, N.Y. 12180
2. E.T.Net
Educational Technology Branch
Lister Hill National Center for Biomedical Communications
National Library of Medicine
8600 Rockville Pike
Bethesda, MD 20894

Appendix: How to join E.T.Net:

1. All you need to do to join is to dial into your local Telenet node via a local phone call. To find the Telenet node nearest you, dial 1-800-835-3638 and tell them where you live and what speed your modem is. They will tell you the correct number to call. Make sure your modem is set to 7 data bits, 1 stop bit, and even parity
2. Dial your local Telenet node telephone number.
3. When Telenet asks for 'TERMINAL=', type, 'D1' and hit <RETURN>
4. When Telenet gives you an '@' prompt, type 'C 301 565' and hit <RETURN>
5. E.T.Net will then ask you to 'Please enter network login:', and you should type 'etnet' <RETURN>
6. Follow E.T.Net's prompts, and when it asks you to enter your last name, type 'newuser' <RETURN> Please note to be sure to type 'newuser' in lower case.
7. Now E.T.Net will take you through a registration process. You are on your way!
8. When you have completed the registration process, E.T.Net will ask you to "JOIN which conference?" Type 'users_guide' now, and E.T.Net will join you to the 'users_guide' conference which will teach you the basic commands you need to know to use E.T.Net. Alternatively, from an AND NEXT? prompt, you can type 'join users_guide' and be placed into the 'users_guide' conference. Once you are inside the 'users_guide' conference, from an AND NEXT? prompt, type 'new' and you will be given an introduction on how to use E.T.Net. If you wish, you can save it and print it out for future reference.
9. After finishing the 'users_guide' conference, from an AND NEXT? prompt type 'join digital_images' to join the 'digital_images' conference where you will be able to participate in discussions relating to applications of computers in radiology.
10. Remember that anytime you are confused by E.T.Net, just type 'HELP' in order to get assistance.
11. When you are done using E.T.Net, type 'bye' in order to logoff.

The TEACHiR™ Project, a Hypermedia Program for the Interpretation of Medical Images

Jonathan Merril

High Techsplanations, Inc., Rockville, MD

Daniel Riordan, Neil Notaroberto and Robert Allman

Department of Computer Medicine,

George Washington Medical Center, Washington, DC

Abstract

TEACHiR is a computerized decision support system that assists in the interpretation of medical images. TEACHiR is an acronym for Thompson's Education And Consultation Help In Radiology. This program will assist health care providers in the formulation of a set of likely differential diagnoses for a given radiologic finding. The program uses the GAMUT system (a system which links radiological findings to differential diagnoses) developed by William LeRoy Thompson M.D., the first registrar of Radiologic Pathology at the Armed Forces Institute of Pathology.

The system is menu driven and user-friendly, prompting the health care provider for a methodical description of the findings that are present on a particular study. Then, the program generates a list of differential diagnoses and displays representative images of each of the diagnoses along with descriptions of each of the diagnoses.

We have completed one section of the TEACHiR program, regarding the interpretation of mammograms. We have selected to work on a system to assist with the interpretation of mammograms for several reasons. First, the mammogram is a very commonly ordered test which has great clinical significance. Secondly, by selecting a narrow field, we will be able to input all of the necessary clinical data into the TEACHiR program (as there is a relatively small subset of disease and non-disease entities that affect the breast). This clinical data will contain definitions, locations, incidence, prognosis, pertinent clinical data, pathology and representative images. Equipped with this additional information, the user can make a much more informed decision regarding the imaging study that he is viewing. We will also evaluate the ability of the software to assist in the diagnostic process by including a computerized survey which will offer both subjective and objective feedback regarding the utility of the program.

Significance

TEACHiR represents an efficient program which can be used to train primary care physician's to recognize signs of pathology in radiographs. In addition to helping the health care provider in the management of clinical cases, this system provides a wealth of information for the student of radiology. A set of valuable rules regarding the interpretation of diagnostic images can be learned through the use of TEACHiR™. The program will provide a valuable complement to existing teaching hospital education resources. Residents who consult TEACHiR will obtain valuable information regarding the interpretation of medical images.

Furthermore, as more radiology systems gain the ability to display medical images on remote workstations throughout a hospital, the TEACHiR program will become increasingly important. The clinician viewing a study which has not yet been interpreted by a radiologist will be able to consult the TEACHiR program to compare the study with the files contained in TEACHiR. Thus, TEACHiR will be the first available on-line help system in hospitals that adapt this new technology.

All of the above information is conveyed to the physician through the use of a single personal computer system. The TEACHiR program represents a cost effective, and convenient manner of presenting this large amount of textual and graphic information through the use of CD-ROM storage media coupled with high resolution displays which are now currently available at a reasonable cost.

Database Construction

Text

In addition to providing a listing of differential diagnoses and representative medical images, TEACHiR will contain an extensive clinical data base. This data base will contain definitions, locations, incidence, prognosis, pertinent clinical data, pathology and representative mammograms. The database will consist of the gamut system as it pertains to the breast.

In order to facilitate the entry of the extensive amount of textual material needed by this program, an optical character recognition program has been used for this task. The software, Accutext™, along with a flat-bed scanner and a Macintosh IICx equipped with eight megabytes of random access memory has been utilized for this task.

Images

The image database has been digitized and stored through the use of a Canon video camera attached to a NuVista 32 bit image capture and display board, and a TrueVision VIDI/O video decoder box which communicates with a Macintosh IICx computer with eight megabytes of random access memory. Images have been captured with eight bits of color resolution, allowing 256 shades of gray.

Software

With the advent of *Hypertext* by Theodore Nelson in 1972, the concept of linking information in unique ways was introduced. A commercial application of this idea was introduced by Apple Computer with their program, HyperCard. Although HyperCard is a powerful tool for the rapid construction of sophisticated software, it lacks the ability to display images that have color or gray-scale. Recently, a program called "SuperCard" was introduced by Silicon Beach Software. This program is compatible with HyperCard; however, it allows for the use of color and gray-scale images. Through the use of SuperCard, we are able to link text and graphical information in a very convenient manner. SuperCard facilitates for the interconnection of graphics, sounds, and text to allow for flexible and creative multi-media computer programming.

Hardware

The immense memory storage requirements of the TEACHiR program will be met by the use of the compact disk (CD) for data storage. These CDs are similar to their music playing counterparts-- however, when they are plugged into a computer, they can instantly access 500 megabytes, of information (2). Five hundred megabytes of information is equivalent to 250,000 single spaced typewritten pages, and as a further analogy, the complete text of the Encyclopedia Britannica consumes only 80 megabytes of text. Thus, a single compact disk can contain all of the information included in six complete sets of the Encyclopedia Britannica (2). The cost of these units continues to decrease and are now available in the \$200 range in quantity. An average radiographic image that is digitized using the method described above takes about 100 Kilobytes of storage space. Thus, a CD-ROM holds 680 megabytes of data is capable of storing 6,800 diagnostic images.

The TEACHiR program will run on a wide variety of hardware. We will have two versions of the software -- one that runs on the IBM PC and the other that runs on the Macintosh computer. For the Macintosh version, the minimum requirements for hardware will be a Macintosh II series computer and a CD-ROM drive. For the IBM version, TEACHiR requires a PC equipped with a CD-ROM drive. For either system, a hard-drive will be advantageous along with a high resolution color display such as a VGA display for the IBM or the standard eight bit color system for the Macintosh. Thus, TEACHiR is designed to run on commonly available hardware.

Evaluation of TEACHiR

Survey

The software will be evaluated for its utility in assisting with clinical decision making in both objective and subjective evaluations. For the subjective evaluation, the TEACHiR software asks the user, if the information provided was complete, helpful, clinically relevant, and presented in a user-friendly manner.

Testing

Furthermore, the TEACHiR program will be evaluated on the basis of testing. Fourth year medical students at The George Washington Medical Center will be provided unknown radiographic cases and asked to render a decision. Two groups will be established, one group of twenty students, will have access to the TEACHiR program and a second group which will not have access to the system. The results of the ability of the two groups to come up with correct diagnosis will be determined and the utility of the TEACHiR program will be assessed. To increase objectivity of the study, the images that are used for testing purposes will not be included in the TEACHiR database.

Summary

The TEACHiR project is being developed in three stages or phases, these phases are summarized as follows.

In phase I, we have completed one section of the TEACHiR program, the section regarding the interpretation of mammograms. This section will include complete the construction of a gamut system for the interpretation of mammograms, as well as the incorporation of representative images of each of the possible diagnoses mentioned in these differentials. In addition, we will provide an on-line help directory which will assist with the diagnosis of each of the radiographic findings. We will also evaluate the ability of the software to assist in the diagnostic process by including a computerized survey which will offer both subjective and objective feedback regarding the utility of the program.

In phase II, we will add additional areas to TEACHiR to include the most commonly imaged areas of the body, providing sufficient information to assist the primary care giver to assist in the interpretation of medical images that comprise the most common diagnoses that are seen by these health professionals.

In phase III, we will market this product to teaching hospitals and large group practices. We will also sell the necessary hardware (CD-ROM player) to increase the potential user base of the software.

We do not intend for the TEACHiR program to replace the expertise of a radiologist in any manner. The TEACHiR program will provide several resources which will enhance the ability of the physician in the interpretation and management of clinical cases. By providing images for comparison, rapid access to medical text books, and providing lists of differentials for a given radiologic finding; the physician will have many valuable tools to help in the interpretation of medical images.

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Digital Radiology Image Learning Library (DRILL): A Standardized Teaching Platform

*Ronald L. Arenson, Robert A. Greenes, Henry A. Swett
and Robert M. Allman*

Department of Radiology, Hospital of the University of
Pennsylvania; Brigham & Women's Hospital, Boston, MA;
Yale University, New Haven, CT; George Washington
University Hospital, Washington, DC

Background

For many years, radiologists have been attempting to keep track of interesting cases, in order to teach medical students, residents, or other physicians, as well as for research purposes. The American College of Radiology (ACR) Index for Roentgen Diagnoses was developed expressly for managing such a teaching file.¹ The ACR Index is organized into two codes, one for anatomy and one for pathology.

One of the earliest "systems" employed with the ACR Index used specially designed manual cards called McBee "keysort" punch cards.² These cards allowed case selection by anatomy or pathology codes by placing a rod through the punched out tabs on the margins of the cards. Those cards that fell away when the stack was shaken were the cards selected. Obviously, large files would present a few difficulties with this approach.

As soon as computers became available in Radiology departments, they were utilized for managing teaching files. One such system used mark sense cards for data collection in order to capture the ACR codes as cases were interpreted by the radiologist.^{3,4} Cases of interest could then be retrieved based on combinations of anatomy and pathology codes. The Radiology Information System (RIS) would then inform the user where the films were stored as well as provide information about the patient (including reports). However, this system does not capture the images or provide any structured teaching.

Computer-assisted instruction (CAI) refers to the use of computers to actually teach. The student can learn at his/her own pace and convenience. Areas of weakness receive reinforcement whereas areas of strength are skipped. Minimal acceptable levels of learning are ensured in a non-threatening environment. Perhaps the most important advantage of CAI relates to the variable ability of students to absorb information. The question and answer mode of teaching in CAI seems to be superior to the more passive learning with textbooks and lectures.

CAI has been shown to be effective in medicine.^{5,6} Teaching residents how to handle relatively uncommon contrast reactions without practicing on real patients is one example of a successful application in Radiology.⁷ However, one of the greatest disadvantages of CAI is the difficulty and increased time for course preparation. Also, students and teachers need ready access to the appropriate computers. Since there is no immediate dialogue between teacher and student, some course materials are simply not well suited for this approach. Anything other than textual material such as pictures or graphics can not be handled other than with an accompanying booklet.

Interactive video adds to CAI moving pictures and sound. Thousands of images can be stored on a single videodisc. Unfortunately, it is very costly to master the videodisc and there are no standards for the videodisc equipment or computer interfaces. The images are no better than video quality which limits the applications in Radiology. The ACR Institute (ACRI) recently began production of a series of videodiscs to make the ACR Learning File available at a reasonable cost. The production techniques utilized for this series maximize the resolution capabilities of videodisc technology and create quite acceptable images for many cases.

Digital imaging has only recently been an alternative to videodisc, as the cost of memory and disks has fallen and as personal computers have become more powerful and available. New laser digitizers create very high-resolution images and displays provide overlay techniques allowing the appropriate labeling of structures on the image. Updating images is quite easy and sophisticated authoring software helps the teacher create new courses. The ability for the teacher or student to manipulate the image (adjust window, level, position) is also a major advantage over videodisc. However, moving pictures can consume much disk real estate and require a more expensive computer. As with videodiscs, there have not been any real

standards in either the hardware or software, creating the situation that requires specialized equipment for each program desired.

DRILL Architecture

In order to overcome the lack of standards in these digital imaging workstations and to build user-friendly yet powerful educational tools, the DRILL program was created as a multi-institutional project with external funding under the auspices of the Radiology Information Systems Consortium (RISC). The overall architecture for DRILL is shown in Figure 1. Conceptually a

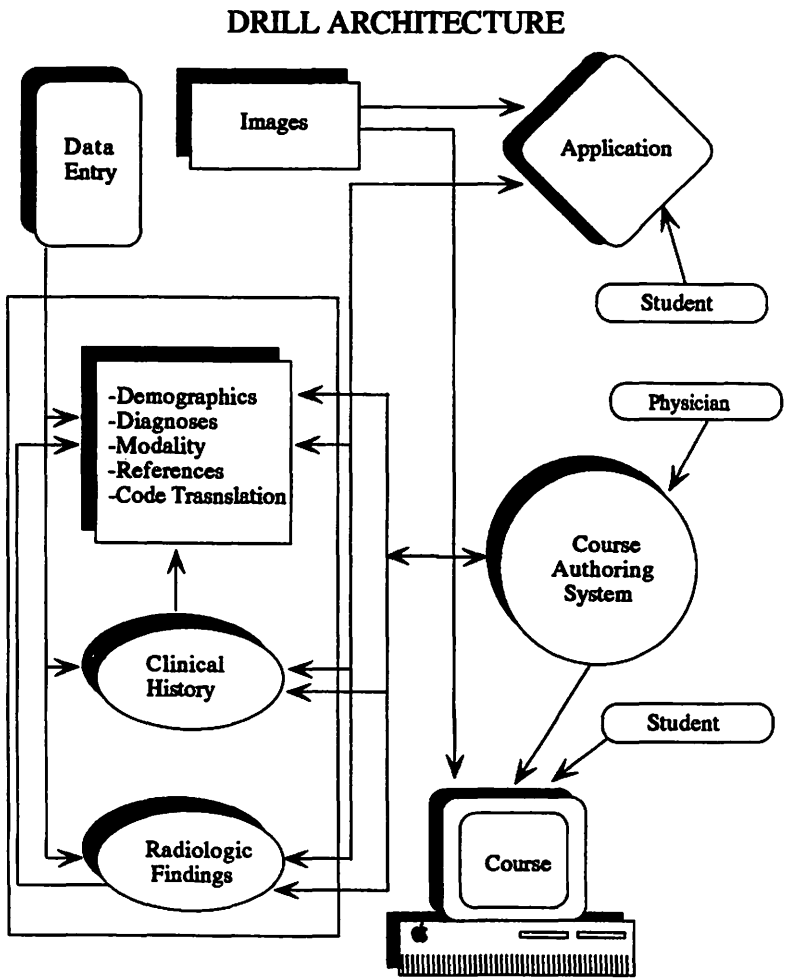


FIGURE 1

relational database contains patient demographic data, clinical histories, radiologic findings, diagnoses, and examination data. This database is linked with digital images, a course authoring system and a set of tools for image display. The database contains modality-specific tables, diagnoses using the ACR code, and references and authors. A commercially available relational database, Oracle, was chosen, to maintain a high degree of compatibility with other developers and systems. For image storage and transmission, the ACR/NEMA⁸ Digital Image and Communication Standard has been adopted in order to again maintain compatibility.

In addition to the standard database, a knowledge domain or semantic net contains information about diseases in a structure that implies classification and provides relationships with other diseases, findings, etiologies, and subordinate entities. Figure 2 demonstrates a segment of such a net with each indent indicating a subordinate term. Anatomical Structure divides from Body Function, Descriptors,

RADIOLOGY NET

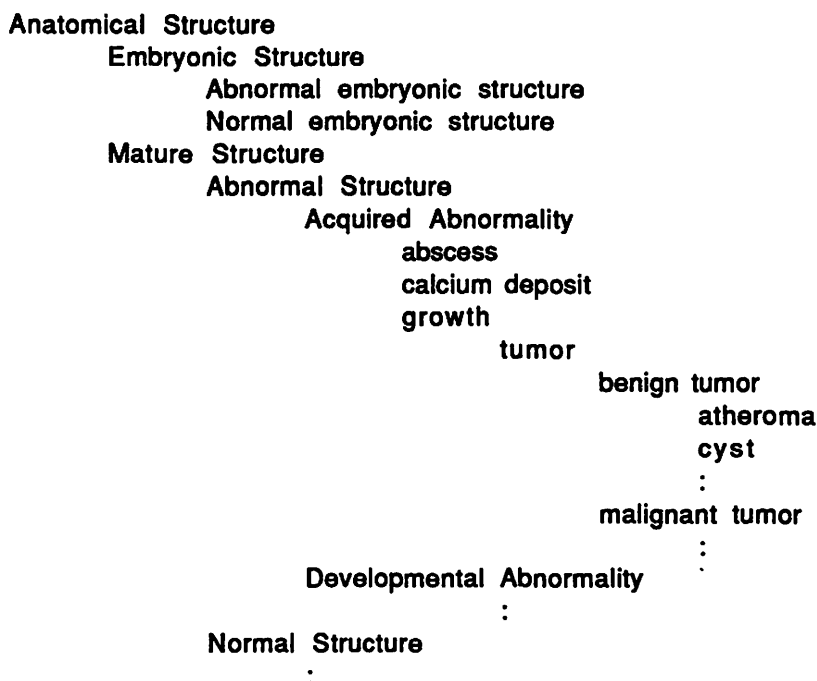


FIGURE 2

Drugs, Finding, etc. Under Anatomical Structure falls Embryonic and Mature Structure. Abnormal and Normal Structure divides both Embryonic and Mature Structure. Abnormal, under Mature, leads to Acquired versus Developmental, etc. This semantic net provides the necessary links among various terms in order to provide powerful searches of the data and image files.

By having the clinical histories and radiologic findings in a structured database, searches are possible on any combination of these categories in addition to simple case selection based on diagnosis code such as the ACR Index. By providing standardized data and image files, display tools, and authoring system, applications programmers can build their own teaching modules while maintaining compatibility with other developers. Teachers will be able to build instructional materials without becoming programmers or requiring their assistance. Students can use the system in either the structured approach, taking a course, or the browsing mode, as described below.

Course Authoring System

In order to create structured learning experiences, a user-friendly set of tools are needed to allow the teacher to create a course. Such courses must provide for sophisticated branching based on answers provided by the student. The teacher must plan the course very carefully, in order to take full advantage of these systems. Incorporating high-resolution images into commercial authoring systems has turned out to be much more difficult than expected.

Browsing Mode

In contrast to the structured learning provided by a course authoring system, students often desire to simply look up a case or cases of a particular disease or showing certain findings. A method of conveniently searching the data and image files, or browsing, is needed to provide this flexible approach. With the semantic net and the relational database, such complex searches are facilitated, allowing the student to gain knowledge in a variety of directions the student may choose to explore. However, this method does not replace the need for structured learning that assures exposure to a certain set of material.

Hardware and software considerations

The hardware platform chosen for this project is the MAC-II (or MAC IIx). Peripherals have been chosen to permit migration to other platforms such as PS/2 and OS/2. The development system contains five Megabytes of RAM, a 16 Megabyte RAM-card, tape drive, ethernet controller, and 1200 baud modem. One 80 Megabyte disk stores data while a 300 Megabyte disk is used for images. Radius display monitors provide 1280 x 1024 pixel images with a grey scale depth of 8 bits. Images are stored at approximately 2000 x 2000 x 8 bits. Most images have been obtained by digitizing xrays with a DuPont laser digitizer, at either 100 or 200 microns per pixel and 12 bits depth in grey levels.

Macintosh Programmers Workbench "C" was chosen to create the display tools and linkages with the various databases and other modules. The Structured Query Language (SQL) interface and Hypercard provide the data entry screens and routines to enter cases into the system.

Project Status

The relational database has been designed, developed, implemented, and tested. The semantic net is still undergoing testing and revisions. The course authoring system is still under investigation, although Course of Action has been tested and partially implemented. The pilot study for DRILL is mammography. Approximately 100 cases have been entered and the images digitized. The use of CD-ROM is also still under investigation, with concerns for speed of image access causing our hesitation, as well as problems with standards in CD-ROM formats.

To date one major application has been built on the DRILL foundation, namely a Magnetic Resonance Imaging (MRI) Simulator. This application not only imitates the console of a GE Signa system, but modifies images in real time to make them appropriate for various pulse sequences. This simulator is used to train technologists without having to use the actual scanner console, which is needed to scan patients 16 hours daily.

Future Plans

After the pilot is completed later this year, we intend to test the mammography module with residents and staff at the participating institutions. Based on success in that trial, additional modules will be added to expand the clinical content. The basic software will be made

available to interested parties for additional projects to stimulate the standards concept.

Another application program planned for the DRILL foundation is the ICON system from Yale.⁹ This expert system provides a series of images to assist in the differential diagnoses. Some images demonstrate similar findings in different diseases, while others show the range of findings associated with a particular disease.

Interfaces with Picture Archive and Communications Systems (PACS) will be created and speech recognition hardware will be added to simplify the user interface, especially for the student. Porting the software to the IBM environment will also be considered.

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Teaching

Computer-Aided Differential Diagnosis in Radiology-Hyperray

M.F. Anderson, C. Barnewolt and D.L. Hudson

Veterans Affairs Medical Center, Fresno and the
University of California, San Francisco, CA

INTRODUCTION

Computer-aided instruction (CAI) has been attempted since the 1960's, first at the public school level, and later at the University level [1]. Interest in application of CAI techniques to medicine is growing [2-9], with much of the effort directed toward nursing education [10-12]. New technology in microcomputer software and hardware has enhanced the ability of medical educators to develop computer-assisted educational programs [13]. The number of simulation programs has also increased [14]. Visually oriented computers such as the Macintosh offer a new approach to medical CAI, in that diagrams, radiographs, scans, and other medical images can be utilized either directly on the computer screen, or in conjunction with videodisk technology [15-19].

Not all efforts in medical CAI have been successful. In one study, investigators found that significant improvement in quality of care occurred with the use of the algorithms, yet improvements tended to disappear quickly when physicians stopped using the algorithms, suggesting that the improvements were due to use of the algorithm and not due to an educational effect. However, learning may not occur if the system provides answers without also providing explanations. CAI programs for medical education using new technological advances are just beginning to be implemented. In particular, medical CAI programs using Hypercard, a new software package for the Macintosh, are in an early stage of development. Some examples include a chest imaging program at Yale created by M.A Swett, a central nervous system program by Carl Jaffe, also at Yale, and an anatomy program by R. Chase at Stanford [20].

CAI offers a number of advantages over traditional teaching approaches. Not all students begin a course of study with the same background, knowledge, and skills. CAI lessons can be tailored to each student's needs, and allows concentration of studies in areas where the student is weak.

The objectives of the project described here were:

1. To develop a teaching aid using the Macintosh computer to instruct residents in techniques of radiological differential diagnosis;
2. To establish a general framework which will allow similar systems to be established for other medical specialties;
3. To evaluate the effectiveness of the teaching aid for resident training.

METHODOLOGY

The Hypercard software on the Macintosh SE was used to establish a framework for teaching radiological differential diagnosis. The resulting program, denoted HyperRay, is an early attempt to provide radiological differential diagnosis on a Macintosh computer which is available to residents in the film reading room. Hypercard offers the advantage of setting up information which is easily indexed by various keys. This allows the student to view the information in an hierarchical structure with different starting points. For example, disorders may be categorized by body location, such as chest, or by functional system, such as bone.

The information is organized into units denoted cards. Each card fills a computer screen. The informational content was determined with the help of a radiology resident. The actual creation of the cards in Hypercard was done by a student assistant. Reference sources include several radiological textbooks [21-23].

Figure 1 shows a sample hierarchical structure with chest as the major division. The program then allows the user to branch to any topic at the right end of the tree. Similar hierarchies exist for other body locations. An icon is provided at the top level. Clicking on an indicated body area will bring up the screen at the top of the corresponding hierarchy. Similarly, hierarchical arrangements by functional systems are also utilized.

Figure 2 shows some sample screens for the bone subsection created with Hypercard. The + indicates that more information is available on that subject. For example, card 5 is obtained by clicking on "Periosteal Reactions" on card 4. This arrangement provides rapid access to details on specific disorders.

The Hypercard software on the Macintosh provides an environment which accommodates the novice computer user while providing sophisticated searching capabilities. An issue which is still unresolved is whether this approach to teaching medical residents will prove more effective than traditional methods. In order to shed light on this issue, the HyperRay program will be evaluated in the resident training setting.

EVALUATION

The HyperRay teaching aid will be evaluated according to the following procedure. The residents will be tested for their ability to read radiographs and provide a differential diagnosis before using the Hypercard program. They will then be trained using the program. After 3 months, they will be re-tested. The testing will be done using a self-assessment program written by Radiology Information Systems Consortium for IBM-PC compatible computers. The program consists of 165 images and usually two sets of five multiple choice questions for each image. The computer automatically scores the test.

FUTURE INVESTIGATION

We plan to expand and adapt HyperRay to provide diagnoses covering all radiological subspecialties and, later, to include brief notes on specific diseases. In the final state, digitized radiological images will be displayed by the system.

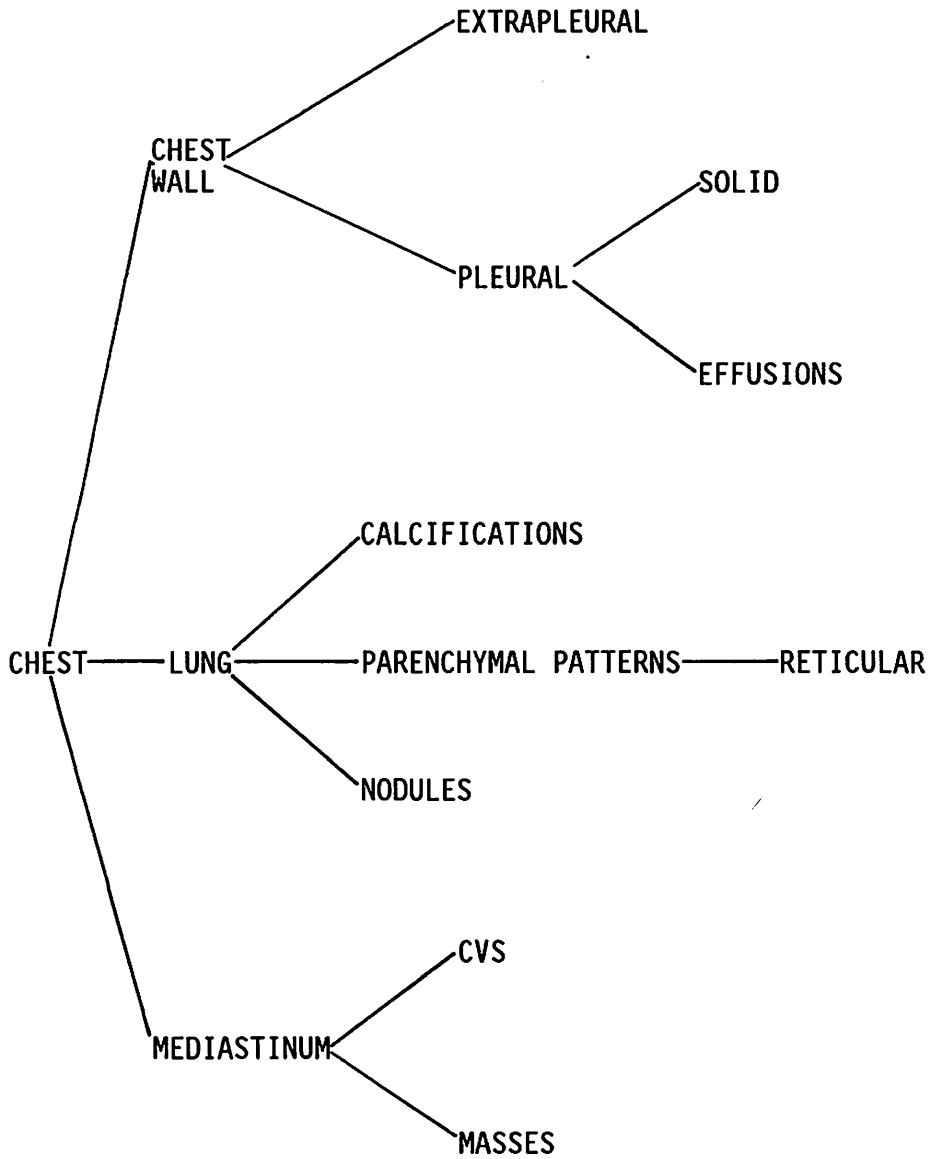


Figure 1: Sample Hierarchy

CARD 4

Index for Bone

- o Osteopenia +
- o Osteosclerosis +
- o Periosteal Reactions +
- o Trauma and Fractures +
- o Localized Bone Lesions +
- o Arthritides +
- o Soft Tissue Calcifications and Ossifications +
- o Skull +
- o Orbits +
- o Nasal and Paranasal Sinuses +
- o Jaws and Teeth
- o Spine and Pelvis +

CLICK ON ANY TERM TO GO TO THAT SUBJECT

CARD 5

Diseases with Periosteal Reactions

- o Malignant Bone Tumors +
 - o Benign Bone Tumors +
 - o Infections +
 - o Arthritides +
 - o Trauma +
 - o Pachydermoperiostosis
 - o Vascular and Lymphatic Disease
 - o Bone Infarcts
 - o Eosinophilic Granuloma, Histiocytosis X
 - o Gaucher's and Other Reticuloses
 - o Thyroid Acropachy
 - o Hypertrophic Osteoarthropathy
 - o Tuberous Sclerosis
 - o Infantile Cortical Hyperostosis (Caffey's Disease)
 - o Fluorosis
 - o Gardner's Syndrome
 - o Idiopathic Degenerative
-

Figure 2: Sample Cards from Bone Section

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Advanced Microcomputer – Aided Medical Illustration

Felix S. Chew

Department of Radiology, Massachusetts General Hospital,
Boston, MA

Martha L. Hefner

Division of Educational Communications, State University of New York
Health Science Center at Syracuse, Syracuse, NY

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In a visually oriented field such as diagnostic radiology, illustrations, diagrams, and other types of artwork can complement verbal description and photographs. Artwork can be of particular value when an anatomic structure or feature is established indirectly. For example, when intraluminal contrast material is used to outline an alimentary tract mass, a drawing of the lesion from outside the lumen or in cross-section may help the reader understand exactly what the contrast material is outlining and why the diagnostic images appear as they do. Artwork may also simplify the description of anatomic concepts and add interest and aesthetic value to a presentation.

The medical illustrator should be involved in the project from an early stage. The information and concepts to be illustrated should be explained in detail to the artist using sketches, specimens, anatomic models, photographs, and so forth. The illustrator can then present the information and concepts in a visual form and create the final artwork. An

initial sketch is made from which successive versions are prepared in concert with the author. When the final version is satisfactory, the sketch is "inked in," resulting in a finished piece of artwork.

The microcomputer is a tool that can be used to transform the visual concept into artwork [1]. The artist, using the computer, can create straight lines, smooth curves, regular geometric shapes, and other elements of graphic design. Most important is the ability to create smooth, curved lines of irregular path and variable weight for executing elaborate drawings. Alterations can be made rapidly and with minimal effort. Although the computer will not transform an artistically maladroit physician into a professional illustrator, in the hands of a skilled medical artist, the microcomputer can rival traditional artists' techniques such as pen-and-ink and color-and-brush in producing high-quality finished artwork for medical illustration.

This article explains the use of microcomputers in the production of a series of medical illustrations for a textbook of skeletal radiology [2].

MATERIALS

The following computer systems and peripherals were used in various combinations: Macintosh II, Macintosh SE, and Macintosh Plus computers with various hard and floppy disk drives (Apple Computer, Cupertino, CA); Laserwriter NTX, Laserwriter Plus, and Imagewriter II printers (Apple Computer, Cupertino, CA); and DEST PC Scan Plus image

scanner (digitizer) (DEST Corp, Milpitas, CA). The Macintosh computers have a mouse which can control the movements of the cursor on the monitor screen with great precision.

The software programs that were used included Illustrator 88 (Adobe Systems, Mountain View, CA), SuperPaint (Silicon Beach Software, San Diego, CA), and Cricket Draw (Cricket Software, Malvern, PA). The descriptions of methods below reflect the use of Illustrator 88 [3-4] running on a Macintosh II with 5 Mbyte of random access memory.

CREATING THE INITIAL SKETCH

Once the graphic concept is clear and the composition of the artwork has been planned, a preliminary rough sketch is made. This sketch may be a freehand pencil drawing, a tracing of a radiographic image, or a previously rendered drawing with adaptations. A digitized version of this preliminary sketch is entered into the computer by way of the image scanner, producing a bit-mapped image. This image is used as a template to prepare a line drawing. The template is traced over with a freehand drawing tool (pen tool) controlled by the mouse and then discarded, leaving only the drawing. An automatic tracing tool is also available where the computer itself prepares a line drawing of the template by tracing the edges. The utility of this automatic tracing tool depends on the intricacy of the original material and the quality of the digitized image.

Radiographic images may be digitized into the computer by use of a video camera digitizer or by scanning high-

contrast photographic prints; the results from either are often unsatisfactory. A more practical method is to trace over the salient features of the radiographic image by hand, using a photograph or the original film, and then digitizing the tracing with the scanner.

It is also possible simply to draw freehand in the computer using the pen tool and other drawing tools without using a template. Such tools are actually computer subroutines for creating straight lines, regular and irregular geometric shapes, smooth curves, and other graphic elements.

MODIFYING THE DRAWING

Once the initial sketch has been compiled, it can be edited, modified, and embellished. A complex drawing is built by layering many individual graphic elements, or objects, on top of each other (Fig. 1). These objects are maintained by the computer as mathematically described objects rather than as bit-maps, a strategy that allows them to be modified and edited by changing their attributes and parameters. For example, a circle may be described by its radius, the location of its center, and the thickness of the line at its perimeter; straight lines have a starting point, a direction, and a length. A circle may be changed in size or location, stretched into an oval, made opaque, or shaded to appear spherical, all within the computer. A line may have any location, length, or direction; it may be changed to any thickness or weight; and it may be solid, patterned, or dashed. Even if layered on top of one another, each individual element of a drawing can be

selected and changed without altering any other portion of the drawing. One can also create composite objects that can be edited and modified together. Objects may be translated, rotated, reversed left for right, inverted top for bottom, stretched, duplicated, enlarged or reduced, and distorted (Figs. 2-3). For example, to create the shadow of an object, one might duplicate the object, give it some angular distortion, make it opaque, rotate it 90°, and translate it to the base of the object. The view of the drawing on the computer screen can be zoomed in or out for detail work or for examination of the overall drawing.

Text can be added to the composition in a wide variety of typefaces and styles; the text can be edited with almost the same flexibility as a word processing program. Text may also be used as design elements and formed into circles or bound along curved paths.

PRINTING THE FINAL VERSION

Object-oriented graphics programs permit the resolution and quality of the final printed output to exceed that of the computer monitor. PostScript (Adobe Systems) is the most common computer language used by high-level art and graphics programs to describe and manage graphic elements through mathematical algorithms. Printers and other computer output devices need a PostScript raster image processor to translate these mathematical algorithms; an output device with such a processor is said to be PostScript-compatible. Such a device is necessary for high-quality output.

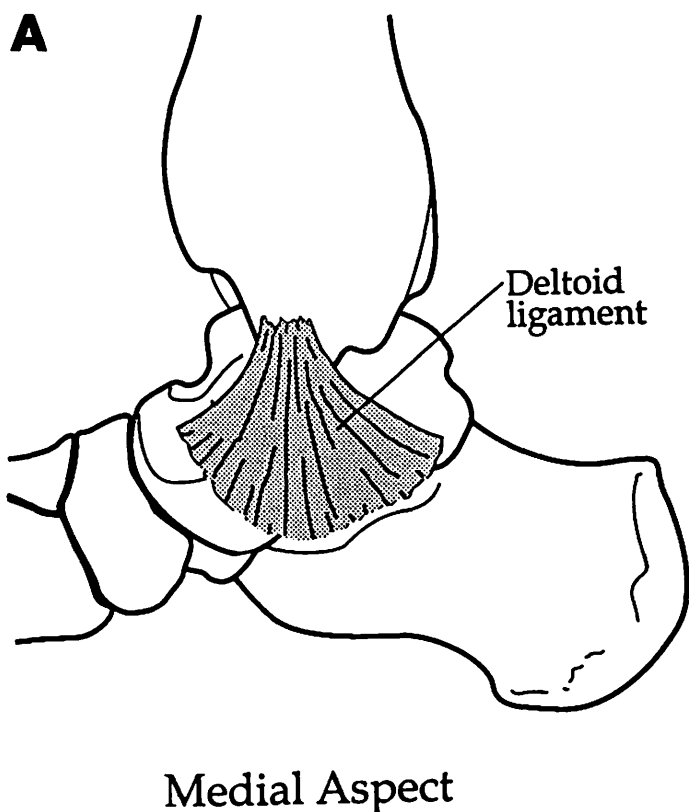
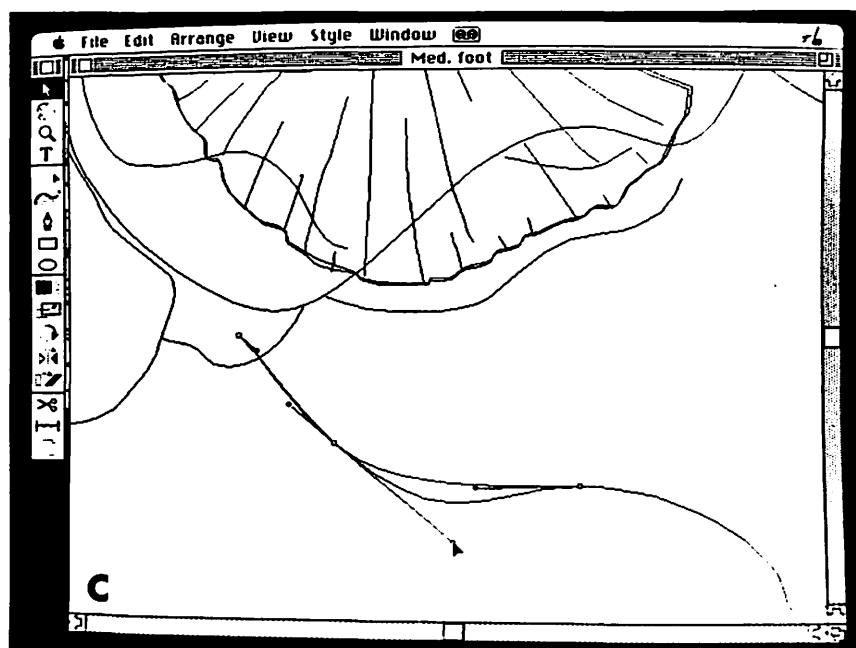
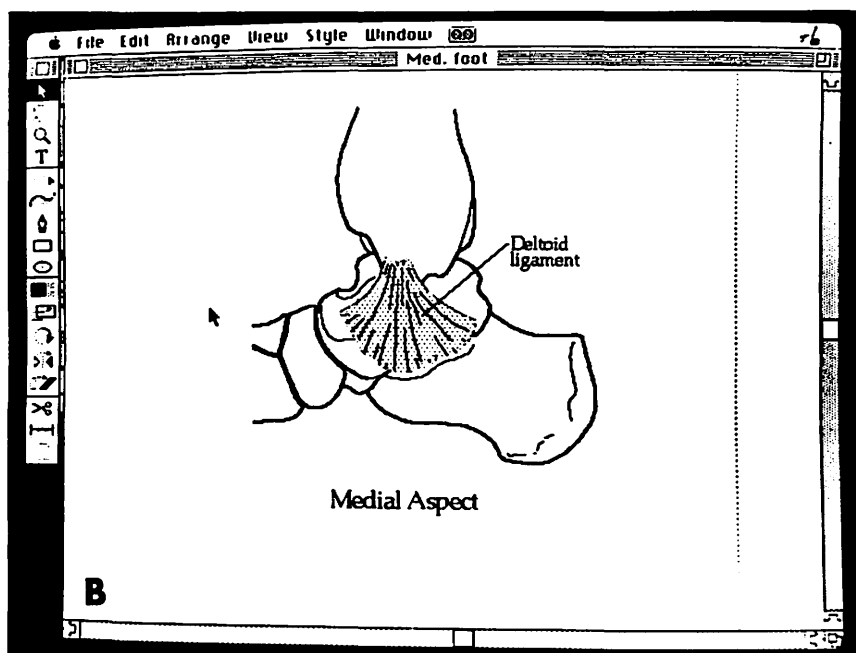


Figure 1. Deltoid ligament of the ankle (Illustrator using Macintosh II). (A) Final output printed by a Postscript-compatible laser-xerographic printer with 12 pixels/mm resolution. (B) Final version as seen on the computer monitor. (C) The drawing on the computer monitor as it is being worked on. The tool box on the left has options for selecting objects, moving them, zooming the view, entering text, and so forth. Additional menus are located along the top. Scroll boxes on the right and at the bottom allow views of different portions of the drawing. Reprinted from *Skeletal Radiology: The Bare Bones* by F. Chew with permission of Aspen Publishers, Inc., © 1989.



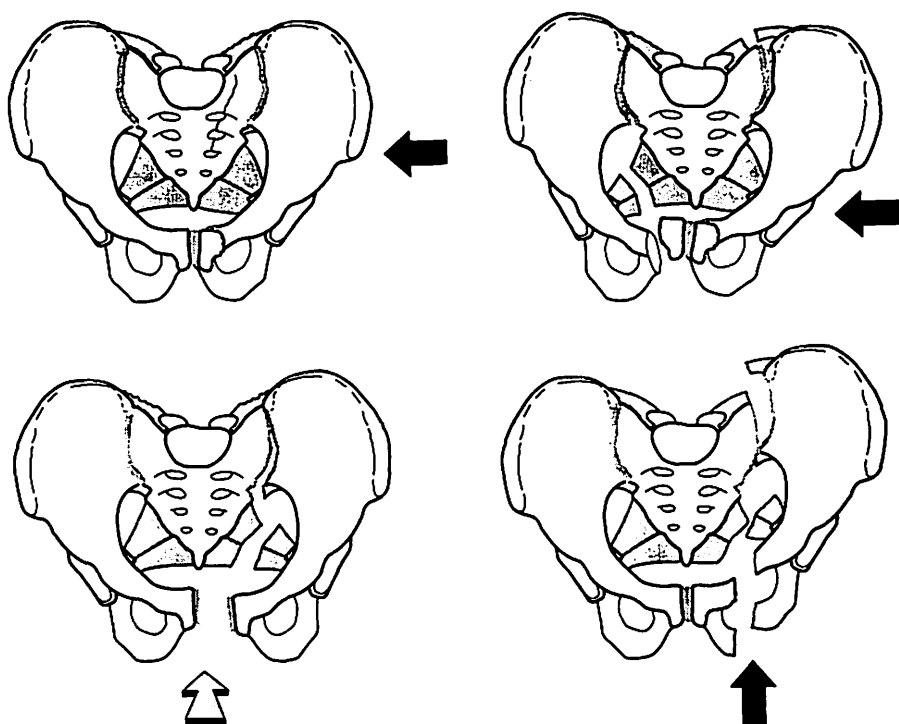


Figure 2. Pelvic fractures (Illustrator 88 on the Macintosh II). This series was created from a single drawing of a normal pelvis that was duplicated and fractured in different ways. Reprinted from *Skeletal Radiology: The Bare Bones* by F. Chew with permission of Aspen Publishers, Inc., © 1989.

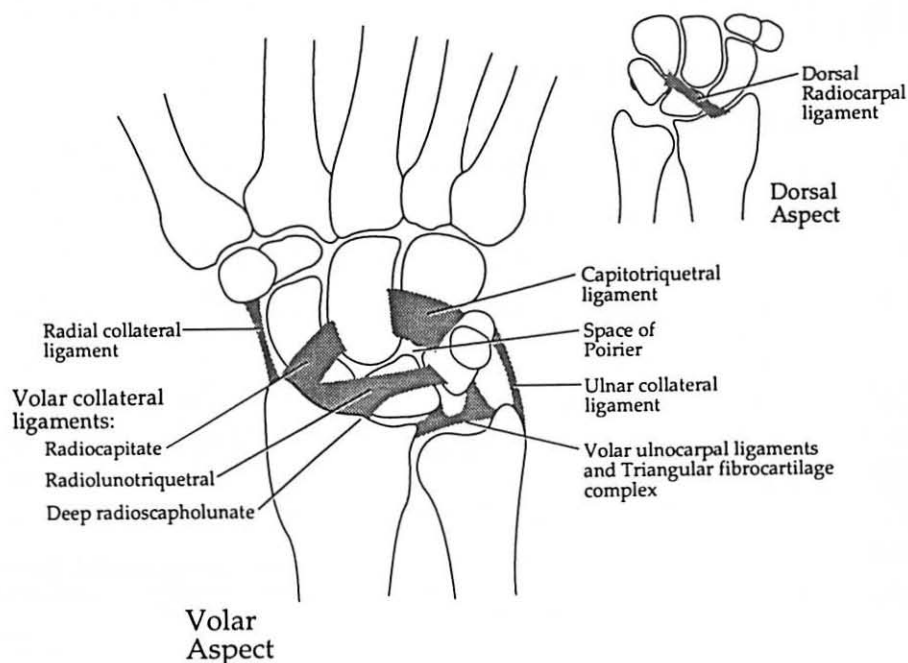


Figure 3. Ligamentous sling of the carpus (Illustrator 88 on the Macintosh II). The inset of the dorsal aspect was created by reversing the basic drawing of the bones, layering the triquetrum on top of the pisiform, and scaling the image down. The line weight and the typeface of the inset and the main drawing are uniform. Reprinted from *Skeletal Radiology: The Bare Bones* by F. Chew with permission of Aspen Publishers, Inc., © 1989.

The final versions of all the drawings in this project were printed by a PostScript-compatible laser-xerographic printer with 300-dpi (120 dots per cm) resolution on letter-size (8.5 x 11 in) 80-lb white coated stock (Vintage Velvet paper, Seneca Papers, Rochester, NY). The artwork was submitted to the publisher as 5 x 7 in (12.5 x 17.5 cm) black and white photographic prints. A total of 60 figure parts were prepared for publication.

DISCUSSION

Several programs for creating art are available for the Macintosh computer. These programs can be categorized into paint, draw, and illustration types. A painting program produces a bit-map on the computer screen. The painting can be edited only by erasing or being painted over. Examples of painting programs include MacPaint II (Claris Corp., Mountain View, CA) and Superpaint (Silicon Beach Software, San Diego, CA). A drawing program produces lines, circles, and other geometric shapes whose attributes (line weight, fill patterns, etc.) can be edited subsequent to their creation. Examples of drawing programs include Cricket Draw and MacDraw II (Claris Corp., Mountain View, CA). An illustration program is one that has a variety of tools, including freehand, drawing, and often painting tools. Examples of illustration programs include Illustrator 88, FreeHand (Aldus Corp., Seattle, WA), and Canvas (Deneba Software, Miami, FL). As these types of programs have evolved, features of drawing and painting have become integrated. The approximate price range for software

programs is from \$100 to \$500. Computer-aided design programs that are intended for mechanical or architectural drawing, where exact dimensioning and scaling is critical, may lack tools for freehand drawing, and are therefore not particularly suitable for medical illustration.

In selecting a computer system for medical illustration, the choice is restricted to the Apple Macintosh by the availability of software. Computing speed is important because of the mathematical calculations involved each time objects are created or modified. Although the dimensions of the drawing are not limited by the size of the monitor, a larger screen size allows more of the work to be seen while drawing. The program Illustrator 88 requires at least 2 Mbytes of random access memory to run properly; many Macintosh systems are supplied with only 1 Mbyte. A hard disk drive is essential because of the large size of the programs and the large size of the files they create. Mouse substitutes such as a drawing tablet with a pencil-like stylus (IS/ABD Input System, Kurta, Phoenix, AZ) may be helpful if one wishes to create the initial sketch by tracing over a picture. The output device of choice is a laser-xerographic printer that is Postscript-compatible. A dot-matrix impact printer has much lower resolution and while it can be used for rough drafts, it should never be used to print the final artwork. Film recorders may accept graphic output for making 35 mm slides. Illustrations from the Macintosh can be output onto a photo imagesetter such as a Linotronics model L300 (Linotype Co., Hauppauge, NY); this would allow resolution as fine as 2540 dots per inch (100 dots per mm).

CONCLUSION

The vast potential of the microcomputer for creating high-quality art and graphics [5-6] is being realized by the availability of high-level illustration programs running on fast computer systems. Although illustrating on the computer is still time-consuming, it is generally more efficient than using traditional artists methods. The chief advantage of the computer is in editing, modifying, and changing a drawing. The computer is not a substitute for a clear conceptualization of the illustration and it will not make a muddled concept clear. It is simply another tool the artist can use to put visual images on paper.

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Development of an Authoring and Tutorial Program

Marvin E. Goldberg and Jack Pejsa

Department of Radiology, University of Minnesota,
Minneapolis, MN

Although there are several authoring programs available, we have developed a combination authoring and tutorial program which allows the author to make provision for interactive instruction, as well as easy links to audio visual aids.

PROGRAM DEVELOPMENT:

The program was developed utilizing Turbo Prolog Version 2.0. The prolog programming language was chosen because of its ease in prototyping and the availability of windowing programs which facilitate the generation of interactive menus and dialog boxes on the screen. Prolog has been used as a prototyping language for other applications. While the resulting program code becomes, somewhat, large, it is still useful, and final development of the program could be carried over into another programming language. The program has been developed for the MS-DOS system and has run successfully on the IBM PS/2 family of computers. It can run from floppy disk drives, although if placed on a hard drive, program execution will be faster and smoother.

DESCRIPTION OF PROGRAM:

The program was developed in two parts. The first part, "Author", is devoted to the authoring program and the second part, referred to as "Tutor", presents the material to the

student. In practice, the two parts would be located on separate disks, and only the tutoring portion would be presented to the student for his use.

The authoring segment of the program is menu driven. Text material which the author desires to be visible to the student is developed in an editing screen which has capabilities common to most word processors. Use of the system is easy for anyone with previous experience with word processing programs. When completed to the author's satisfaction, the text material can be saved to disk. Similarly, questions in the form of multiple choice or true/false questions, can be generated easily by the instructor and also saved in their own separate files. The sequence of presentation of the text screens and question screens can be edited by the instructor and rearranged at will. All such material can be saved to disk for further use. At the present time, the program does not drive visual aid hardware, but provision is made for development of an interactive module for use with video disk player.

The tutorial segment, which is the only segment visible to the student, prompts the student for his name and choice of program to view. The program presents text screens and questions in the order selected by the author of the program. For each question screen, the student may elect to receive immediate feedback as to his correctness of answering the question, or can elect to proceed without such feedback. In any event, all responses are recorded by the program and at the completion of the session, the student is informed of the number of correct responses. This information is also permanently recorded on disk by the program for review at a later date by the instructor.

This program was developed with the aid of a grant from the University of Minnesota Health Sciences Learning Resource Center.

A Personal Computer Based User Interface for Viewing & Manipulating Digitized Radiographic Images for Instructional Applications

Lincoln D. Stein, Jan Snyder-Michal and Robert A. Greenes

Decision Systems Group, Brigham and Women's Hospital,
Boston, MA

Abstract

We have designed a user interface for the display and manipulation of radiographic images that is intended for use in digitized teaching files and computer aided instruction (CAI) applications. By making the way the viewer interacts with a set of digitized images on the computer screen as similar as possible to the way he interacts with conventional films on a viewbox we have tried to create a system that combines the directness of the conventional teaching file with the power and flexibility of CAI.

Introduction

The conventional film-based teaching file has long been a mainstay of radiology education for medical students and residents. As a teaching tool, it has the distinct advantages of simplicity and directness. The teaching file is a direct link between the way the student examines and manipulates radiographic images during training and how he will do so during his professional career: the images appear on radiographic film and are manipulated by moving the films around on a viewbox.

Recently there has been a great deal of interest in creating teaching files and film libraries that are linked to a computer database [1,2]. Under such a system the database could be searched by criteria such as anatomic site, features, diagnoses or imaging modality in order to quickly identify relevant radiographs. Of the various methods available for linking a computerized database to a film library, the most direct way is to create a digitized image library in which images are stored in digital form on magnetic or optical disk where they can be accessed and displayed directly on the computer screen. This brings the potential capabilities of rapid access to large libraries of high-quality images without the disadvantages of the conventional teaching file.

The major tradeoff of the digitized image library versus conventional film is that the radiographs are displayed on a video display terminal rather than in their native form, changing the nature of the

interaction between the viewer and the image. Manipulations that are routinely done with film-based radiographs, such as brightlighting underpenetrated areas, circling interesting features with a grease pencil, or, in some cases, using a magnifying lens to study fine details, are not possible under most digitized image display systems.

We feel that it is desirable to make the learning experience as close to actual practice as is feasible. Recently we have prototyped a user interface for image presentation that accomplishes this on readily available personal computers.

The Interface

There are five elements of our interface which are described below. An authoring and presentation system incorporating these features, as well as other hypermedia and knowledge management capabilities, has been developed in our laboratory. This system, known as Explorer-2, is implemented on the Macintosh II computer [3, 4].

1. The "Viewbox"

In Figure 1, two digitized mammograms have been placed next to one another in a single window which acts as a virtual "viewbox". Like a real viewbox, the images can be picked up and moved around to different positions. To do so, the user positions the mouse-controlled cursor on the image he wishes to move, depresses the mouse button, and drags the image to the desired position. Releasing the mouse button drops the image into place. This makes it easy to place PA and lateral films side by side or to arrange a series of films chronologically.

2. Brightness and Contrast Controls

Two sets of controls are associated with each image; they appear to "float" over the image and can be moved about or made invisible at the user's discretion. These controls appear as the rectangular areas at the top and left margins of the left-most image in Figure 1.

One set of controls in each image is the pair of horizontal arrow sliders shown at the top of the left-hand image. These controls graphically show the user the amount of contrast and brightness in the image and allow him to adjust these parameters as needed, changing the global appearance of the image. This permits selective highlighting of specific image features. When multiple images are displayed on the viewbox simultaneously each has its own brightness and contrast controls, allowing the viewer to compensate for differences in film technique.

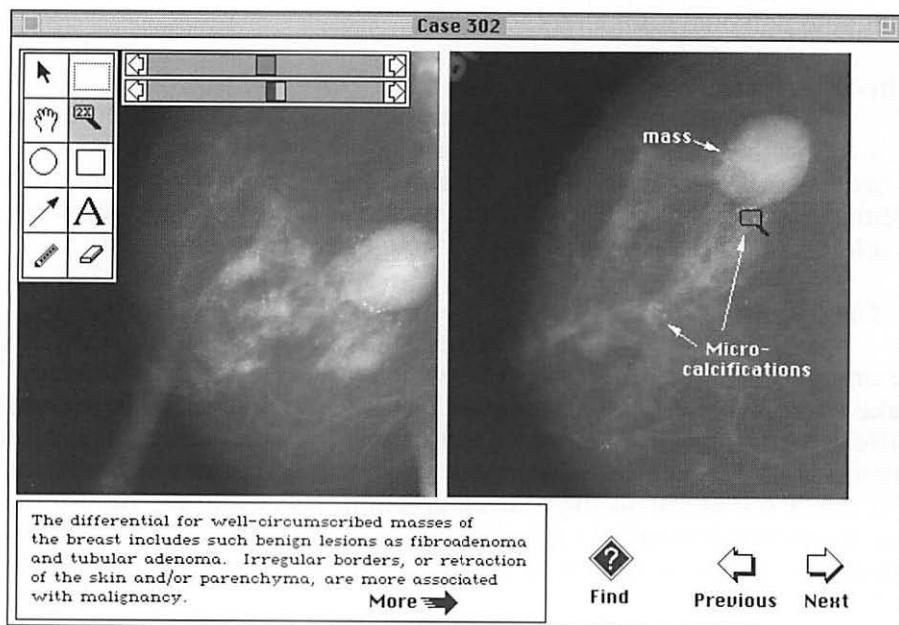


Figure 1: Elements of the user interface. The digitized images of two mammograms are shown side by side in a single window. The images can be moved around, overlapped and resized with the mouse. Textual and graphical information can be added to the images as overlays. As described in the text, the two rectangular panels in the upper left of the leftmost image represent controls that allow the user to change the contrast and brightness of the image as well as to select various tools with which to manipulate the images. Text and graphics can be overlaid on the image, as shown at the right. Blocks of text and hypertext can be placed elsewhere within the window, or in other windows. A portion of a hypertext block can be seen underneath the leftmost image. In the example shown here, the user has positioned a small “magnifying lens” cursor over a portion of the image on the right that contains a feature of interest (calcifications), the magnification of which is shown in Figure 2.

3. The *"Magnifying Lens"*

The group of symbols or "icons" along the left border of the image defines a set of tools that allows the user to manipulate the image in several ways. To select a tool, the user positions the cursor on the desired tool and clicks on it with the mouse.

One of the most important of these tools is the magnifying lens, represented iconically as a miniature hand-held lens. When the magnifying lens tool is selected, the on-screen cursor that is linked to movements of the mouse turns into a small picture of a magnifier (this cursor is present in the center of the left-hand image of Figure 1). The user positions the cursor over some point of the image and presses the button on the mouse. At the moment the mouse button is depressed, a rectangular window pops up over the area selected and displays a magnified view of the image. This pop-up magnifying window is shown in Figure 2. While the mouse button is depressed, the user can move the mouse in any direction and the window containing the magnified image will slide over the fixed unmagnified image exactly as if the user were holding a true magnifying lens to the image. When the user releases the mouse button, the magnified image instantly disappears. The rapidity of the appearance and disappearance of the magnifying window allows the user to examine multiple regions at high magnification without losing his orientation and without performing a feat that would be "unnatural" with real film, as for example, making the entire image larger.

It is important to note that the magnified image produced by the magnifying lens tool represents true, full-resolution image data rather than false magnification through interpolation or replication of pixel values. The data produced by commercial radiograph scanners has approximately four-fold greater resolution than can be displayed on the screen of a personal computer. The magnifying lens gives the user access to that high resolution data in a natural way.

The magnifying lens tool's magnification can be adjusted by the user by issuing various keyboard commands, allowing the user to scan through the image at low magnification and zoom in to high magnification to see very small details.

4. The *"Bright Light"*

Depressing a designated key on the keyboard puts the magnifying lens into "bright light" mode, a setting that increases the local contrast and brightness of the image shown within the lens. This approximates the effect of holding an overpenetrated section of the film up to a bright light in order to provide a virtual bright light facility without changing the overall brightness and contrast of the entire image. Like the magnifying lens itself, this technique allows the user to scrutinize

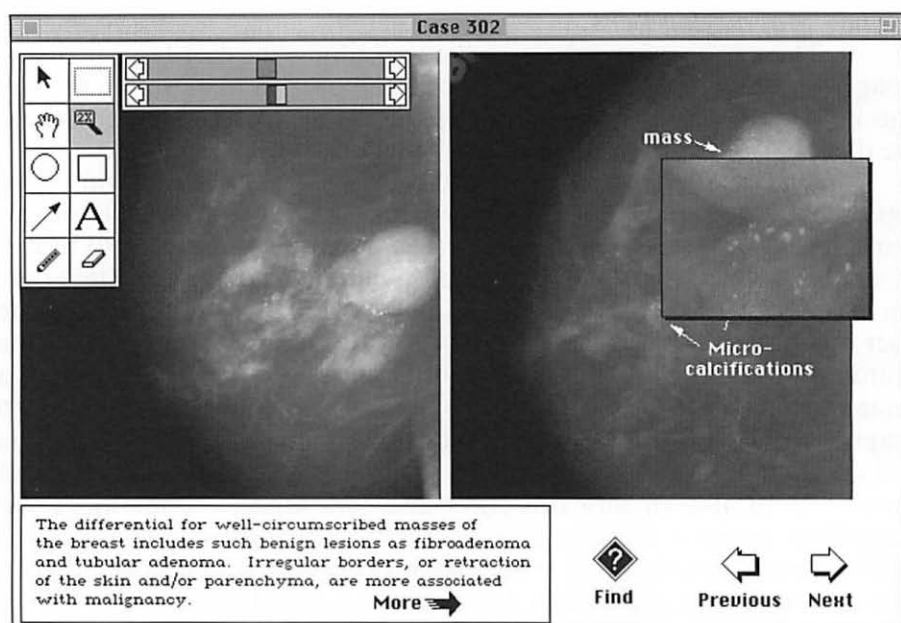


Figure 2: In this figure, the user has pressed the mouse button while the “magnifying lens” cursor was on the region shown in Figure 1. A rectangle has popped up showing greater detail in the region the user selected. As the mouse is moved around, this rectangle slides over the image, magnifying the portion beneath it. The user can change the degree of magnification, so that even greater detail can be examined. By depressing a designated key, the user can also locally increase the brightness within the area of magnification, achieving a virtual “bright light” facility.

an area of interest without changing the surrounding landmarks. The bright light mode can be applied while the magnifying lens is displaying the image at increased magnification. Alternately, the magnifying lens can be set to "1X" (no magnification) so that the bright light facility can be used without adding magnification.

5. The "Grease Pencil"

Other icons represent a group of graphical tools that substitute for the grease pencil. Using these tools, the user can "mark up" the image in any arbitrary screen color, erase portions of the markings, and save and discard the set of markings to disk at his discretion. The markings are treated as a graphical overlay distinct from the actual image information, making it possible for different users to make different markings on the same image.

Among the grease pencil tools is one that allows free hand markings to be made as well as an eraser for making free hand revisions. In addition to these, there are tools that allow users to draw circles, ovals, rectangles, lines and arrows, as well as a tool to insert textual information such as captions and comments.

Conclusions

We have designed a user interface for the display and manipulation of digitized radiographic images that overcomes the problem of the unnaturalness of the computer-displayed image. By mimicking the way that people interact with film, the interface combines the power of the computer with the flexibility and naturalness of film reading.

Our interface displays digitized images that look and behave like film. The images can be moved about and overlapped on a virtual viewbox, marked on with a grease pencil and other graphic tools, selectively enlarged with a virtual magnifying lens to give the user access to the full resolution of the original radiograph without losing his global orientation, and selectively brightlight areas of overpenetration. In addition, contrast and brightness controls allow the user to alter the image globally in order to highlight specific image features. It does this on a readily available personal computer running in a software environment specifically designed to produce computer-aided tutorials.

Acknowledgements

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A Radiology Hypertext System for Resident Education & Clinical Decision – Making

Charles E. Kahn, Jr.

Department of Radiology, University of Chicago, Chicago, IL

Hypertext is a means of organizing information which allows one to explore a topic by utilizing the connections among various related pieces of information. "Fact/File" is a developmental system that provides hypertext access to a wide variety of information of interest to radiologists and radiology residents. This system has been implemented as a module of the MARS radiology information system at the University of Chicago Medical Center.

The system is organized as a collection of "frames." Each frame consists of one computer screen of textual information about a specific topic, such as a disease entity or a radiological differential diagnosis. Each frame is indexed alphabetically by keywords in its title. To view a particular frame, the user enters a word or part of a word from the frame's title. By entering only one letter, the user can view all frames whose titles have words beginning with that letter.

The frames also can be accessed through a hierarchically arranged topical index. In the first level of the index are the organ systems, such as "Gastrointestinal (GI) system." If the user selects this topic, a sub-index appears; this menu contains choices such as esophagus, stomach, liver and pancreas. If the user selects "stomach" from this list, the user can choose from categories such as congenital disorders, neoplastic disease, and inflammatory disease.

One can create "links" between frames which allow a user to move easily among related frames. For example, while exploring the differential diagnosis of "thickened gastric folds," the user can move immediately to the discussion of Ménétrier disease without returning to the index. The user can then return to the previous frame (the default), pursue another sub-topic, or exit to the index.

The system presently contains about 800 frames which discuss radiological gamuts as well as relevant anatomy, physiology and pathology. The data are very compact, and require less than 250 kilobytes of storage. The programs are written in the ANSI-standard MUMPS programming language. Radiology residents and attendings can use the system at all times from terminals located throughout the radiology department. Information is retrieved and displayed instantaneously.

The Fact/File system is a simple, MUMPS-based hypertext system that can be integrated into a clinical radiology information system. Because physicians can explore the system without leaving their work area, the system is useful as a desktop reference and an educational tool, particularly for radiology residents.

MAMMO/ICON: Voice Activated Intelligent Radiologic Image Display

Paul R. Fisher, Pradeep G. Mutalik, Ian Maddison, et al

Department of Diagnostic Radiology, Yale University School of Medicine,
New Haven, CT

ABSTRACT

An integrated system for computer-aided diagnosis and reporting of mammographic examinations has been developed, utilizing both an image database and a rule-based medical advice generator. MAMMO/ICON is designed to minimize the radiologist's time and effort, by automatically delivering context sensitive advice as a natural byproduct of the report dictation process.

To use MAMMO/ICON, case findings and preliminary diagnostic conclusions are dictated into a voice recognition report transcription system. This generates a standard radiology report that can be printed right away. At the same time, clinical and radiologic findings are passed to MAMMO/ICON for analysis.

MAMMO/ICON works in the background to produce two fundamentally different forms of advice. Written text includes evidence in favor of, or against the radiologist's hypothesis or other competing diagnoses, in computer-generated prose, immediately after the case has been dictated. The output format depends directly on the degree of agreement between MAMMO/ICON's analysis and the radiologist's conclusion: significant differences are highlighted with supporting evidence, while agreements are tersely noted. Selected images are displayed using a modified form of IMAGE/ICON, which displays known examples of each diagnosis being considered, as well as a dynamic atlas of radiologic features, organized along one dimensional maps called axes.

We believe that successful computer-based advice systems in radiology will deliver relevant information at the time of reporting, when it is most useful. Mammography is a growing portion of our radiologic workload, and involves subtle feature detection and expertise in interpretation. MAMMO/ICON represents one approach to develop tools that facilitate proper film interpretation in this challenging field.

INTRODUCTION

As the modern practice of Radiology grows more complex, clinical radiologists find they are overwhelmed by the amount of information available in, for

example, journals and new texts. The addition of new imaging modalities has only added to the burden of the radiologist who is trying to keep abreast of the relevant literature. This has fostered the development of sub-specialities within radiology, but even sub-specialists find daunting the effort needed to practice state of the art radiology.

The demand for mammographic services has exploded over the past ten years, as clinicians become aware of the utility of early, pre-clinical detection of breast cancer, and the excellent benefit/risk ratio achieved by modern film-screen and xeromammographic technique(1). However, only a small fraction of the women who fit the American Cancer Society guidelines for regular screening are currently being screened; as that portion grows, mammography will assume a larger portion of the radiology work schedule. In addition to stand-alone breast imaging centers and mobile vans, group practices and hospitals are expanding their mammographic services, and thus more radiologists will be required to interpret mammograms. Mammographic expertise will thus be in demand, especially since errors in mammographic reading are particularly costly- whether they be errors of over-sensitivity (and thus too many unnecessary biopsies) or over-specificity (and missing some cancers within their early, potentially curable phase). This demographic shift is reflected in the recent addition of a mammography section in the American Board of Radiology oral examination.

Mammographic interpretation involves subtle feature extraction, complex characterization and localization of abnormal features, and coherent decision-making based on those features, and thus expertise is typically attained only after considerable clinical experience. Recent developments in artificial intelligence techniques offer the potential to design tools to assist clinical decision-making, and thus permit a relatively inexperienced radiologist to perform radiologic interpretation at a consistently high level of competence(2). ICON/LPD is such a system designed for the diagnosis of chest film abnormalities in patients with lymphoproliferative disease(3). This paper will describe MAMMO/ICON, an expert system based on our experience with ICON/LPD, designed to assist in the interpretation of mammographic images.

One key stumbling block to the development and use of medical expert systems has been that they typically make the physician spend precious time and effort to utilize them; in general, it takes several minutes to type in a description of a case, and often the system asks for information in an unfamiliar form, or requires a search through the patient's medical records. Physicians in general do not have the luxury of leisurely pondering their routine cases, and thus may be willing to tolerate a low (albeit non-zero) level of uncertainty in individual cases, in order to keep up with a demanding caseload. For example, a radiologist may not recall the specific chest film findings seen with paragoniasis, but when confronted with such a clinical question, will often not feel the need to consult reference material if the chest film appears normal, or is consistent with his or her general understanding of parasitic disease in the chest. We propose that expert systems such as the ICON series will be accepted into the day to day clinical practice of radiology only when they require essentially no extra time and effort by the radiologist, and that they offer their information as the case is being reviewed and dictated by the radiologist.

Recently, a number of commercially available voice recognition systems have been placed on the market, some designed specifically for medical transcription. These systems are trained by the physician to recognize his or her own voice, from a vocabulary of medical terms. Some systems allow word for word transcription, and some also employ "trigger phrases", which are predetermined abbreviations for blocks of text. For example, the phrase "Normal chest" might be translated into "The heart, mediastinum, lungs and bony thorax are normal." MAMMO/ICON uses such trigger phrases to smoothly interface with the radiologist; as a case is dictated into the transcription system, the trigger phrases are sent to the expert system for analysis. Its conclusions are displayed, available at a glance if the radiologist so chooses, and requires no additional effort or time from the busy clinician. For routine cases, the expert system may be ignored, and since it resides in a separate computer, it does not affect the performance of the medical transcription system. In difficult cases, the radiologist may directly query the expert system, such as to display known examples of a given diagnosis, or to see the differential diagnosis of a particular radiologic finding.

SYSTEM ARCHITECTURE

MAMMO/ICON contains three program modules, which are linked to each other. The voice recognition module is a commercial medical transcription system (Voice-Rad, Kurzweil Applied Intelligence, Waltham, MA), and which runs on a 386-based microcomputer. The other two modules run concurrently on a second microcomputer (Macintosh II; Apple Computer, Cupertino, CA). The two microcomputers are linked by a serial port cable. The system requires 4 megabytes of memory, and is configured to use two high resolution 19-inch color monitors (1024 X 768 X 8 bits of display for each monitor.) The images were digitized by means of a Konika film digitizer, and by a 24-bit color frame grabber board (RasterOps). Images and the knowledge base are stored on a magnetic hard disk, and on a WORM drive (Write Once, Read Many optical drive).

The Image display module is written in the C language (MPW C; Apple Computer), and the Critique module was written in Lisp (Allegro Common Lisp, Coral Software, Cambridge, MA) The software interface for connection of the voice transcription system and the expert system microcomputers includes a commercial utility (PC Anywhere).

SAMPLE OUTPUT

MAMMO/ICON was designed based on our experience with IMAGE/ICON, which has been described previously(3,4). Many of the system features are derived directly from IMAGE/ICON; this paper will focus primarily on those features unique

to MAMMO/ICON.

The rules-based expert system in MAMMO/ICON first analyzes the demographic data of the case, and determines if that patient is in a high, intermediate, or low risk category for developing breast cancer. For example, advanced age is associated with breast cancer development, so an elderly woman is, a priori, at an increased risk, whereas women under 30 rarely develop breast cancer (unless there is a strong family history). Once the risk category is determined, the radiographic features are analyzed, and the diagnostic hypothesis offered by the clinician is compared to the expert system output. As described previously, MAMMO/ICON assembles fragments of prose (from the set of rules whose predicates were satisfied by the facts of the present case) into coherent sentences, paragraphs, and themes. This assembly is performed by PROSENET (5), a set of utilities designed for text generation, based on augmented transition networks. MAMMO/ICON also selects a set of images from a large image database, which are related in some critical way with the case at hand, and displayed in several different modes. The most powerful mode is AXIS Display, in which images are aligned in rows, which have selected and ordered the images according to a set of well-defined criteria, such as the differential diagnosis of a given case, ordered from malignant to benign. We currently have 5 display axes, including the HYPOTHESIS axis (which illustrates proven cases of the clinician's hypothesis which are similar to the present case), SPECTRUM axis (which illustrates the entire range of appearances of the hypothesized diagnosis), BENIGN/MALIGNANT axis, (which order diagnoses based on their malignant potential), and SIZE/EXT. axis, (which orders lesion by their size), as well as the DIFFERENTIAL DIAGNOSIS axis. The radiologist can easily change the hypothesis on the case, and generate a new set of reference images.

For example, an elderly patient obtains a mammogram, which demonstrates a dense stellate mass, with associated nipple retraction, and adjacent skin thickening. The radiologist could dictate this case using trigger phrases, which would generate a standard mammographic report. At the same time, MAMMO/ICON would examine the trigger phrase content, and display a critique of the case, based on its set of rules in this domain, as illustrated in figure one. The text of the critique reads:

While Mammo-icon will attempt to illustrate teaching points relevant to the case you have entered, it's output must be viewed only as a general guide, and good clinical judgement is, as always, the key to proper radiologic diagnosis.

Because this patient has significant risk factors for breast carcinoma, this critique is being modified to reflect her increased risk. Any woman with a positive personal history of breast carcinoma, a close relative with breast ca, or any elderly woman should be considered to be at increased risk.

You have suggested carcinoma as your primary diagnosis in the given case. Mammo-icon has located relevant facts on the following diagnoses (based on your patient's clinical and radiographic features): carcinoma and chf. According to Mammo-icon's analysis, the diagnosis of carcinoma is strongly supported by the following factors.

First, a dense mass with unsharp or spiculated borders is always suspicious for a malignancy, and since your patient is in a high risk group, you must assume it is malignant unless you have clear evidence of a specific benign diagnosis.

Second, your patient demonstrates skin thickening associated with a mass. Malignant tumors can often do so by causing lymphatic obstruction.

Third, nipple retraction, as in this case, may frequently be caused by a malignant process.

After a general introductory paragraph, the critique assesses the patient's risk factors, and assigns her to a risk category, in this case high risk. The next paragraph summarizes the radiologist's hypothesized diagnosis, and whether MAMMO/ICON agrees with the hypothesis. The critique then explicitly recaps the reasoning behind its analysis, by reporting those rules that influenced the current case analysis.

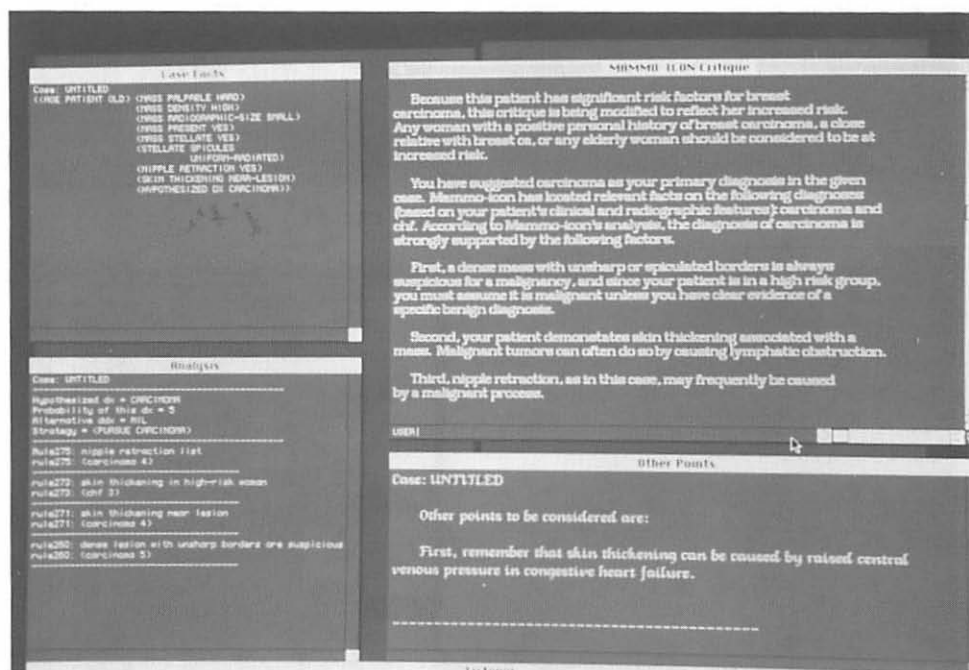


Figure 1. Text output of MAMMO/ICON

Images are then selected to illustrate the system analysis, as demonstrated in figure 2. Note that a classic image of a stellate mass with associated skin thickening is displayed as a full-size image, since it was the most similar to the described case, and each of the five axes has many images to display. On the other hand, if a low density mass with a clear capsule is dictated, the axis display, as shown in figure 3, would be much different; only 2 images appear in the DIFFERENTIAL DIAGNOSIS axis, because the only reasonable diagnostic possibilities are lipomas and oil cysts.

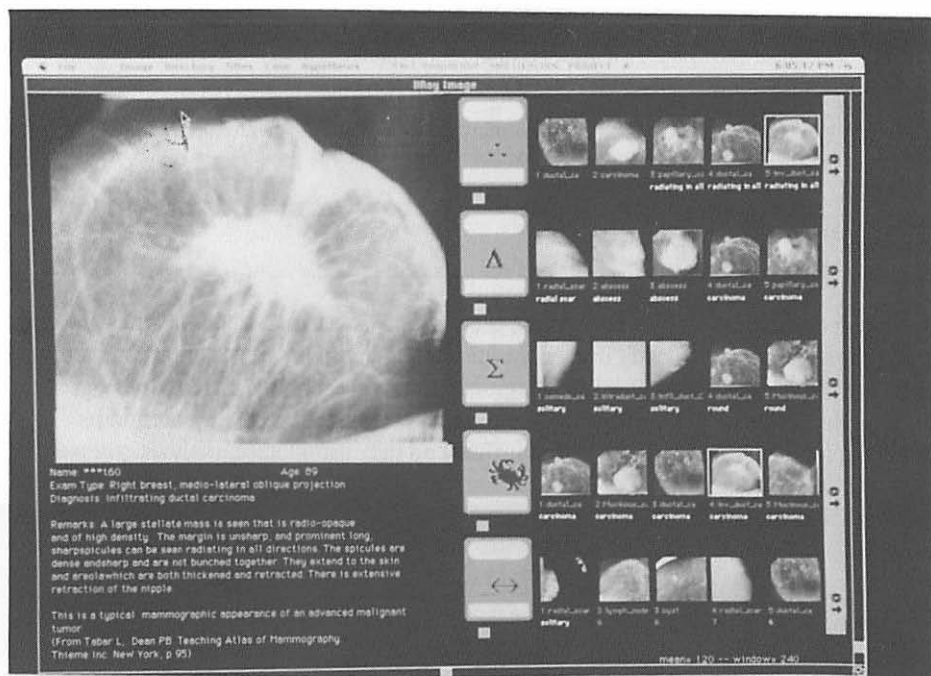


Figure 2. Image output of case #1



CONCLUSION

The MAMMO/ICON system demonstrates that expert systems for assisting in medical decision-making may be designed to fit unobtrusively in the workday patterns of clinicians, so that with a minimum of effort and time they may render assistance, even as the case is being dictated. As we have gained experience with expert system development, it became clear that the field of Medical Artificial Intelligence has at least two hurdles to clear to gain full acceptance for our projects. First of all, these systems must be medically accurate and reliable. No less importantly, the interface must be as automatic and clear as possible, or the computer terminal will sit unused in a corner of a room. Our guiding metaphor was that of a friendly colleague, blessed with perfect memory, who sits by our side as we dictate, and to whom we can turn, in moments of uncertainty for a quick consultation. MAMMO/ICON demonstrates that this is technically feasible at present, and we predict that this approach can only become more effective as new, improved voice recognition systems become available.

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TNM v2.0: A HyperCard Stack Used to Track the Staging of Lung Cancer Patients

James Hornig-Rohan, Peter Dietrich and John Tampas

Department of Radiology, University of Vermont, College of Medicine,
Medical Center Hospital of Vermont, Burlington, VT

Abstract

This paper describes the development of TNM v2.0, a HyperCard stack that is used to track the staging of lung cancer patients at the Medical Center Hospital of Vermont. In its first iteration the program consisted of a single HyperCard card that contained five fields and a number of buttons. Functions concerned with maintaining the stack and with producing reports were performed manually prior to the development of TNM v2.0. With the development of the second generation of this stack these functions have been automated and delegated to buttons. The user interface was "tuned" to allow a graphic-user interface (GUI) that is more "Mac" and HyperCard-like to make use of the program easier for those already familiar with the Macintosh GUI. Once a basic Macintosh HyperCard version of the program was developed, the GUI was improved to provide the user with feedback in the various steps of the Lung Cancer Staging work-up. When the user is performing a TNM analysis context-sensitive help regarding the data that make up a particular T, N or M class is available. Diagrams demonstrating the sites of the various lymph nodes on CT are available to assist with the correct nodal classification. A final portion of this program, which assists in the day-to-day work-up of a lung cancer staging, involves the generation of reports. Prior to this version of the program, reports were generated by simply printing out each patient card relevant to that week's lung tumor committee meeting. As work on this HyperCard Lung Cancer Staging database system progresses, more of the Macintosh GUI will be utilized to assist the radiologists, medical oncologists, radiation oncologists, pulmonologists and radiology residents in their day-to-day work with staging and follow-up on these patients. The final stage of the project will involve networking all of the clinicians, pathologists and radiologists who participate in the multidisciplinary staging.

Background

The workup of lung cancer patients in the Radiology Department at the Medical Center Hospital of Vermont is tracked in a HyperCard database that we refer to as TNM version x.x.x. The name comes from the first letters of the words Tumor, Nodes, Metastasis and the term is used throughout the field of medicine to refer to the staging of a cancer and the version x.x.x refers to version number of the program in use at the time. There are different TNM classification schemes for each of the different varieties of cancer. A patient is entered into the database as soon as one of the chest radiologists becomes aware of the patient with a possible lung tumor. From this point on the entire workup of the patient can be tracked. The TNM database program can generate reports for use in the radiology department, for the attendings involved in the care of the patient, for the tumor registry and for use in the weekly lung tumor conference. The program allows for data entry to be performed by using many of the HyperCard metaphors that the user should be familiar with from having used a Macintosh before. Staging of the patient's tumor can be performed with assistance from the computer with *help* being available for each T, N, and M that is used to generate the final stage. Some form of the program has been in use for over a year in the Radiology Department at the Medical Center Hospital of Vermont and the current version has been in use since December of 1989. The program is used to assist in coordinating the activities of the multidisciplinary lung cancer staging and treatment group that meets each Tuesday morning.

Method

TNM was developed using the HyperCard programming environment from Apple Computer, Inc. External commands and external functions (XCMD's and XFCN's) are used to give the program the added capabilities needed to generate reports and for some portions of the user interface, such as the displaying of dialogs. TNM uses a linked list of data cards to maintain the patient database. Generic navigation cards are used to steer the user through the database. Moving through the database or stack is performed by clicking on buttons and whenever possible standard or familiar icons were selected.

The linked list structure was chosen because it was fairly easy to set up using HyperCard. The HyperTalk script that sets up the linked list is located at the stack level and a portion of this script is displayed in Figure Six. The linked list is maintained by storing the ID of the previous card and the next card in a hidden field called linked-list which is present on each card. The ID of the previous card is placed in the first

line and the ID of the next card is placed in the second line. This could easily have been done using the first and second items of the first line or some other variation of storing the card ID as a variable within a hidden field. At present the linked list is not sorted and a master list of members of the linked list is not maintained. If search time ever became too great these may represent options that could increase performance of the system. The last card in the patients set of data cards informs the user that no further data cards are available for that patient. All data for a patient is written onto a shared background of one of three different cards. The first screen seen by the user when opening the program is shown below in Figure Two. The user has initial control of the database from the panel of buttons; choices are made by "clicking on a button." Clicking on a button refers to the process of placing the mouse on the button and then pressing the button one time. Each button has a program or HyperTalk script associated with it. The names of the buttons are self-explanatory in most cases. AM-Report refers to the Tuesday morning multi-disciplinary lung tumor conference where members of the Medical Oncology, Pulmonary Medicine, Radiation Oncology, Thoracic Surgery and Radiology departments meet to discuss the current lung tumor cases. The Film list button generates the film pull list that is used by the film library staff to pull the films for set-up on an alternator for the Tuesday morning multidisciplinary lung cancer staging and treatment conference where members of the Medical Oncology, Pulmonary Medicine, Radiation Oncology, Thoracic Surgery and Radiology departments meet to discuss the current lung tumor cases.

```

set up the linked list fields on each card.

-- set the linkedList field of pt demographics
card
if debug is "true" then
  answer "Setting the linked list of
  demographics card"
end if
go to ptCard
put thisCard into line 1 of field linkedList
put tm1Card into line 2 of field linkedList
put currentPt into line 1 of field ptNAME
put currentMRN into line 1 of field ptMRN
put currentDOB into line 1 of field DOB
put the short date into field date
-- set the linkedList field of card tm1
if debug is "true" then
  answer "Setting the linked list of 1"
end if
go to tm1Card
put ptCard into line 1 of field linkedList
put tm2Card into line 2 of field linkedList
put currentPt into line 1 of field ptNAME
put currentMRN into line 1 of field ptMRN
put currentDOB into line 1 of field DOB
put the short date into field date
-- set the linkedList field of card tm2
if debug is "true" then
  answer "Setting the linked list of 2"
end if
go to tm2Card
put tm1Card into line 1 of field linkedList
put stagingCard into line 2 of field linkedList
put currentPt into line 1 of field ptNAME
put currentMRN into line 1 of field ptMRN
-- put currentDOB into line 1 of field DOB
put the short date into field date

```

Figure One

The buttons in the lower right-hand corner allow the user to get *help*, turn menus off or on, and return to the previous card. These functions are symbolized by standard HyperCard icons.

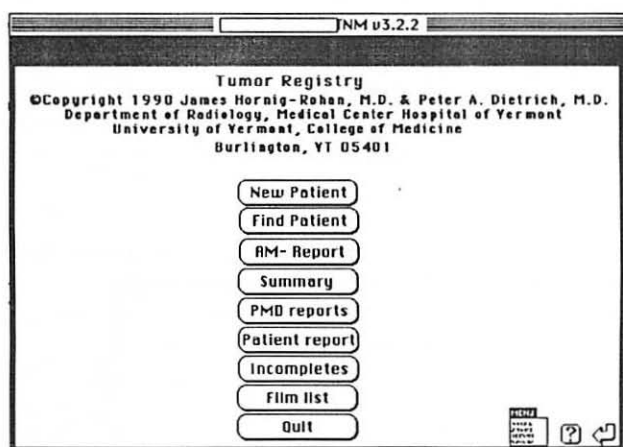


Figure Two

When the user selects the New Patient button the user is prompted to enter the patient's name, medical record number and date of birth. After these have been entered the user gets the first patient data card or screen which is presented below in Figure Three. This card acts as the summary card for the patient's current workup. Patient identity information is entered by the software into each identity field present on each of the patient's data cards. There are three fields for entering the names of referring or primary doctors caring for the patient. These function either as pop-up menus or as text fields. This type of user interface for data entry was chosen because many of the patients are

Figure Three

referred from a fairly limited group of physicians. These same physicians are listed in the physician database that the program uses to generate the addresses for the physician reports. In the bottom right-hand corner of the card displayed in Figure Three are a number of buttons. Each button was selected in an effort to have the icon present on it represent the function which it performs. From left to right these buttons perform the following: printer button brings a dialog box asking which of three different types of report you would like to print for this patient; writing hand button brings up the dialog to add this patient to the film lists; the left and right arrows move you to the previous or next card containing this patient's workup; and the return button has a variable function depending on where in the data entry process you select it. On

Figure Four

the patient data entry cards it returns you to the start-up card; from the start-up, TNM assist or Film List cards it will return you to the previous card. The buttons in the Work-up tracking of section of this card bring up a series of dialogs that answer questions relevant to the workup.

Figure Five

Figure Six

These range from asking the date a study was performed to whether or not useful data was obtained from the study. Figures Four and Five show the two workup cards that make up a patient database. Navigation buttons are shared between these two cards and they perform the same function. The TNM button brings up the card shown in Figure Six.

This card is used to assist with completing the TNM and staging of the patient's lung tumor. The user clicks on the proper *T*, *N*, or *M* button and the computer places that value in the *T*, *N*, or *M* field on the bottom portion of the card. The button *Stage by Computer* runs a computer staging algorithm when it is clicked. The user is then presented with a dialog asking whether or not the staging information generated by the computer should be placed in the doctor staging field. The data in the *T*, *N*, *M*, and the doctor staging field is then transferred to the blanks on the patients clinical data form for cTNM, if TNM was selected from the clinical card, or in sTNM and pTNM, if TNM was selected from the surgical/pathology card, along with the relevant staging information. The *left*, *right* and *return* arrows function as described above. Each of the choices possible for *T*, *N*, or *M* has a question mark button located next to it on the screen. This question mark button is used to allow the user to view the current definition of the *T*, *N*, or *M* at the time that the program was put together. Revisions in these definitions would require revising the help and most likely the staging that results from selecting a particular combination of *T*, *N*, or *M*. Near the mid-portion of the card is a section labeled *Zones*. This is present to assist the user in remembering to enter the distribution of lymph nodes involved in the tumor. User entries from the *Zones* button are placed at the end of the line of text in the *N* field on the TNM card. Data present in these fields is transferred to the relevant card along with the rest of the staging data when the user presses the *Return* button located in the lower right-hand corner of the screen. TNM stores all of the data regarding a patient's workup on three cards. Each card is copied from a master set of cards having a different background. After being copied the ID number of the card is then placed in the linked-list hidden field present on each of the three cards, as described above. Only the information that is specific to each patient is different stored in the foreground. Scripts that can be called from one or more places in the program are all located at the stack level. This was done in an effort to conserve code space. The final portion of the program to be described here is the Film-list. A sample film list with the patient information blanked out is presented in Figure Seven. The film list is generated so that the film library staff knows which films need to be pulled from the shelves and placed on the alternator for review at the Tuesday morning lung tumor conference. At the same time the film list also maintains an abbreviated record of the workup of the patient. This is useful to the film librarians because it provides a fairly accurate portrayal of the studies that the patient is

undergoing in case the film is not located where the Hospital's Radiology Film Library Database says it should be located. Data in each patient's section of the film list also provides a brief summary of the current status of the patients workup as well. The printout produced by the film list printout handler or procedure also serves as a useful tool for collecting additional data for entry into the database as a result of the conference.

SesameStreet:TNM v3.2.2

Radiology AM Tumor Conference List 2/20/90

Patient: [redacted] MRN: [redacted] DOB: [redacted] Workup: Staging
Chest CT 12/14/89, Bone scan 12-22-89.

Patient: [redacted] MRN: [redacted] DOB: [redacted] Workup: Staging CT
done 1/22/90.

Patient: [redacted] MRN: [redacted] DOB: [redacted] Workup: Phantom
Nodule Study

Patient: [redacted] MRN: [redacted] Workup: Chest CT 1/90.

Patient: [redacted] MRN: [redacted] DOB: [redacted] Workup: Staging CT
done 1/17/90.
Bronchoscopy biopsy done 1/17/90.
PFT's FEV1 = 1.63 were done. Barium swallow done 12/6/90

Patient: [redacted] MRN: [redacted] DOB: [redacted] Workup: Staging CT
done.
Lung Bx done under fluoro 2/15/90.
Head CT done.

Number of patients: 9

Figure Seven

The film pull-list is also used by the radiologist running the Tuesday morning multidisciplinary lung cancer staging and treatment group as a means of having the patient data handy in a useful format. Complete data on the patient would be available either from the paper record or from the database.

Summary

TNM is a HyperCard database written to track the staging workup of patients with lung tumors. The program assists the user in data entry by reducing the amount of typing necessary to enter data and by using HyperCard metaphors to ease the data entry process. A multitude of enhancements to the current version of the program are planned and these include: production of summary reports, downloading of pathology and other reports from the Hospital's main frame, tutorials on staging and working up a lung tumor, an optical database to assist in staging, networking of the members of the multidisciplinary staging and treatment group and further enhancements to the report generating XCMD's and XFCN's currently being used. The program will be made available from the Chest Radiology Division where requests for the software should be directed.

Research

Quantitative Ultrasound Imaging

Joie Pierce Jones

Department of Radiological Sciences, University of California, Irvine,
Orange, CA

PULSE-ECHO ultrasonics has become, in recent years, an important and widely accepted method for non-invasive imaging of the human body, especially for fetal, cardiac, and abdominal applications, and appears to offer great potential for further developments in diagnostic medicine. Results in varied clinical settings have shown medical ultrasound to be an accurate, versatile, and inexpensive technique yielding cross-sectional tomographic images with negligible risk or discomfort and with reasonable resolution.

The present success of ultrasound has been realized through the utilization of only a small portion of the information actually available in an echo waveform. All ultrasound systems now in routine clinical service provide data on only two tissue properties: back-scattered echo strength and the average attenuation in the medium, neither of which is separated experimentally and neither of which is measured quantitatively. That is, present systems are based on envelope detection methods and therefore are capable of displaying only echo-amplitude (i.e. intensity) information. Thus, a conventional A-scan displays the intensity of the echo waveform as a function of acoustic travel time (i.e. depth) and a conventional B-scan produces an ultrasonic mapping in which the spot intensity of the display is related to the echo intensity.

Phase information (such as the sign or polarity of the echo waveform) is recorded by the transducer, which is a pressure sensitive device, but is not utilized in present display or measurement schemes. Other parameters such as the spectral characteristics of the echo waveform are also easily obtained but are not utilized in present ultrasound systems.

Because the interaction between sound and even simple tissue structures is an exceedingly complex process, a vast amount of additional information, besides the echo intensity, is potentially available from the ultrasonic waveform. In principle, in-vivo techniques could be devised which would extract and separate the medically significant features of the ultrasound interactions with tissue and would display ultrasonic tissue signatures appropriate for a differential diagnosis. The development of such quantitative techniques for the measurement of ultrasonic tissue parameters and/or the display of ultrasonic tissue signatures is now receiving considerable attention from the research community (1-4).

Of course, the mere realization that not all measured data are used for image construction does not, in itself, guarantee that the discarded data contain new or non-redundant information. Occasionally, there is also an understandable confusion between the achievement of a "better" (e.g. higher resolution, more displayed dynamic range, etc) image, and the development of techniques that generate perhaps even rather poor images with an intrinsically different (tissue) information content. This last point can be illustrated without attempting to accurately define the concept of "information" displayed: there is an intuitive appreciation of the differences between a high and low resolution ultrasound reflectivity map of tissue (as crudely displayed in a conventional B-scan) on the one hand, and a reflectivity map and an attenuation image, on the other. The former two attempt to portray the same intrinsic tissue information, but to different degrees of fidelity. The latter two differ markedly in their "information content" quite irrespective of the relative resolution, or fidelity, to which they may individually be obtained.

Projections of the ultimate utility of future information extraction techniques have ranged from the ludicrously optimistic to the crushingly pessimistic. It is our contention that a realistic assessment may be made by looking to the physics of the ultrasound/tissue interaction. In this manner, a better appreciation of the range of information amenable to probing may be obtained. This is a vast field for investigation, and we shall heavily circumscribe our treatment. What cannot be answered here is the medical utility of the extracted information: this is a problem that only protracted clinical trials can resolve.

Ultrasound Information Extraction

The basic medical ultrasound imaging "experiment" may be essentially described as follows: an input ultrasound wave is generated, which is allowed to penetrate into tissue, where it interacts. Waves generated by this interaction, including the modified, emergent incident wave are detected outside the tissue. The aim is to make some statement about the tissue from measurements on (a subset of) the emergent waves ("OUT") and a knowledge of the incident wave ("IN"). Tissue is thus an "OUT.IN" relationships. This description is virtually identical to that used to define scattering experiments and it is immediately clear that scattering theory will play a fundamental role in our analysis.

Given the fact that it is a medical ultrasound investigation, some details can be added to the above description. The input field is likely to be a longitudinal pressure wave, with a frequency in the 1-10 MHz range; for most applications, a pulsed field will be employed--broad band, but with a central frequency well within the indicated range. In principle, there is no difficulty in assuming the incident wave to be accurately known. There can be less certainty about specifying the (acoustic) nature of tissue. It is clearly an inhomogeneous medium, varying in both space and time, the latter often manifesting itself as an approximately cyclic variation of properties. Tissue is very richly structured, with spatial correlation lengths spanning a wide spectrum, well beyond the wavelength scales of the so-called "diagnostic" frequency range. Ultrasound attenuates fairly rapidly within most soft tissues at a rate that is definitely

frequency-dependent. Since there is some experimental evidence to support the idea that shear waves do not propagate over significant distances within soft tissues, it is probably reasonable to describe the wave as a propagating pressure wave. Experimental techniques are not, in general, sufficiently sophisticated to unambiguously detect non-linear effects within tissues at the moderate power levels and frequencies employed for imaging, and there is thus no compelling reason, at present, to resort to the added complexity of non-linear theories. Soft tissues certainly scatter ultrasound waves and it is known that scatter-generating structures consist of fluctuations in at least the density, compressibility and ultrasound absorption parameters. The relative strength of scattering from these sources, as well as the overall scattering strength, are not known, but it is generally assumed (if only for computational convenience) that the scattering is, in some sense, weak. Soft tissues exhibit a complicated composition and a complicated thermodynamics, and, in some cases at least, are clearly not isotropic media: the significance of these factors has not been fully assessed in most applications and we disregard them, for simplicity in the following. Many of the acoustical properties of soft tissue change with disease, and this ultimate diagnostic potential of ultrasound provides one of the most exciting areas for investigation.

It seems clear that there are basically three classes of information that can be extracted about soft tissues via ultrasound probing: some statement can be made about tissue acoustical properties (such as attenuation, impedance, etc.), or about tissue structure (i.e. the spatial distribution of the acoustic parameters), or about tissue dynamics (i.e. the temporal distribution of the acoustic parameters). In practice, methods for achieving that end may be conveniently classified into three types of technique: non-quantitative imaging, tissue characterization, and quantitative imaging. We now discuss each of these techniques with particular emphasis on quantitative imaging.

Non-Quantitative Imaging

Conventional pulse-echo imaging maps the location, but not the type, of the scattering (reflecting) structures. In all commercial ultrasonic imaging systems, the backscattered echo sequences are envelope-detected, with amplitudes (which can range well over 100 dB) compressed into the dynamic range of the human eye and conventional display devices. Image frame rates with real-time systems are sufficiently high to allow spatial movements of structures to be studied, either qualitatively, or more quantitatively by using special (in fact, simpler) techniques such as M-mode recording. The typical pulse-echo image is an intensity map, devoid of phase or spectral information, with brightness related only very crudely to scatter strength. Attempts have been made at artifact reduction, gray-scale reallocation, resolution enhancement and utilization of multiple images in order to clarify information latent in the image. Most of these attempts are foredoomed to failure, since they neglect to consider that tissue information displayed in a pulse-echo image is corrupted by scanner design and signal processing options, as well as by machine settings. Many non-conventional pulse-echo imaging techniques also fall into this category by virtue of the fact that they produce a non-quantitative image, although sometimes based on an information content other than the echo intensity. Such qualitative

imaging schemes include (1) various methods to incorporate spectral information into a B-mode format, such as spectra-color ultrasonography and the so-called dual-frequency scanning, (2) methods to incorporate phase information into a B-mode format; and (3) various novel techniques for interrogating tissue and receiving the echo waveform.

All of the methods just mentioned, regardless of information content or display technique, produce qualitative images, i.e. images in which no single parameter or combination of parameters is recorded or measured in a quantitative and/or absolute fashion.

Although conventional (qualitative) pulse-echo imaging has become an important imaging modality for diagnostic medicine, it is clear that further advances will largely depend upon the quantitative utilization and display of the ultrasound information.

Tissue Characterization

Ultrasonic tissue characterization includes all techniques and methods which seek to extract and separate from an interrogating ultrasonic wave the medically significant features of the ultrasound interactions and to display ultrasonic tissue signatures appropriate for a differential diagnosis or some other medical purpose. To be useful or significant, such signatures or measures must be related to tissue pathology or physiology. Tissue characterization is broad in scope and, in certain cases, can include aspects of both qualitative imaging and quantitative imaging. At its simplest, tissue characterization involves merely a re-display or recombination of pulse-echo image information in a way that is more pathology specific. Such simple approaches are likely to be of limited value, since they also tend to be machine (and operator) specific. In its most useful form, tissue characterization extracts a quantitative and intrinsic measure describing the spatial and/or temporal variations of any mixture (known or unknown) of tissue properties. The interactiveness between, but distinct separateness of, quantitative imaging and tissue characterization should be evident. Thus, observations in tissue characterization may lead to new imaging schemes which, in turn, may lead to additional tissue characterization. In a sense, quantitative imaging may well be the precursor to truly successful tissue characterization.

It is convenient to separate tissue characterization into the three general approaches which can be taken: parameter estimation, structure characterization, and dynamic characterization. Parameter estimation seeks to measure (or estimate) the value of a particular acoustical property, such as impedance, attenuation, or velocity. The estimate, of necessity, provides an averaged or mean value of the parameter over some region, which can vary in size from the dimensions of the interrogating pulse to a complete A-line. In many cases, the parameter is assessed with respect to one or more variables (for example, attenuation can be measured as a function of frequency).

Structure characterization seeks to extract some index or signature which characterizes the spatial arrangement of small-scale scattering structures, or their

strengths. Clearly, such signatures must correlate with tissue type and/or pathology. In practice, structure characterization often degenerates into a search for structure in the echo waveform rather than structure in the tissue, making the relationship to tissue structure much more nebulous.

Finally, dynamic characterization seeks to characterize the time-dependent behaviour of tissue. Ultrasound methods are particularly suited to this type of approach being capable of monitoring tissue responses and motions on a rapid time scale.

Quantitative Imaging

We use the term quantitative imaging to refer to those techniques which map the distribution and strength of a single ultrasound/tissue interaction parameter (or, at least, a well defined, invariant combination of such parameters), in a truly quantitative way. These methods are largely experimental at present, especially those relying on scattered signals for input.

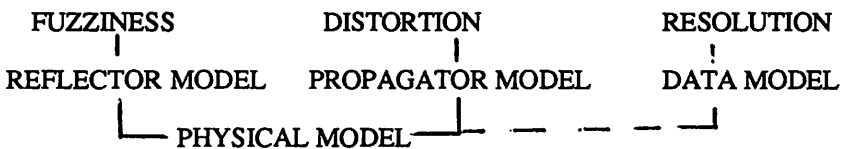
Conventional pulse-echo B-mode images, despite their medical usefulness, are not quantitative images for two reasons. First, their image densities depend rather strongly on system settings and the choice of transducer. Second, even if such system artifacts could be allowed for, the resultant image would essentially be a reflectively map of tissue. Unfortunately, reflectively is a complicated function of both tissue interaction parameters as well as tissue morphology. The quantitative image, in principle, will not suffer from these defects: it would be independent of system settings and scanning procedure, and the image density will relate directly to an intrinsic tissue property uncomplicated by geometrical considerations. In this sense, the quantitative ultrasound image presents a new dimension of tissue information. However, quantitative imaging also demands elaborate data acquisition arrangements, as well as extensive computer-based manipulation of the acquired data.

Two major approaches to quantitative imaging are being developed: transmission imaging and scatter imaging. Ultrasound computerized tomography, based on X-ray CT and utilizing the transmitted ultrasound waveform, has generated both attenuation and velocity maps of tissue (5-7). The velocity images are produced by inputting time-of-flight measurements into the reconstruction process; attenuation images are produced by utilizing measurements of the amplitude of the transmitted signal. Due to the presence of bone and air, these techniques are limited (perhaps fundamentally) to a few body sites such as the female breast or the neonatal head. Ultrasound computerized tomography is more subtle to implement than the X-ray case, since a number of simplifying approximations, such as straight-line propagation, isotropy, and even scalarity of interaction, do not hold in all ultrasound situations. Measurement of the transmitted ultrasound field is complicated by the coherent nature of the generating and detecting devices commonly used. Despite these difficulties, reasonable quantitative attenuation and velocity breast images have been obtained in-vivo but it is as yet too early to assess their true diagnostic impact.

The second approach to quantitative imaging, which we term scatter imaging utilizes the scattered signal to produce quantitative maps of tissue interaction parameters. All scatter imaging methods (and many have been proposed) are related to classical inverse scattering techniques. Here, the problems are formidable and the methods have rarely been applied in-vivo. The proliferation of scatter imaging techniques may be conveniently classified by their data acquisition methods. Diffraction tomography (8,9) and its many variants (including filtered back-propagation) (10) is characterized by the measurement of the scattering into all angles. Impediography (11,12), including its variant, reflectively tomography (13), is characterized by the measurement of the backscattered signal only. Wave extrapolation imaging (14), utilizes what may be termed retroscattering, i.e. scattering into a relatively small cone about the strictly backscattered direction. This classification by data acquisition method is, in fact, dictated by the physics of the ultrasound/tissue interaction. Thus, each class of techniques will be expected to measure different parameters (or combinations of parameters) of the interaction, while variants of a given technique are merely different approaches towards mapping the same parameter.

All quantitative scatter imaging methods are nothing more than specific realizations of special solutions to the inverse scattering problem. The first step in solving such a problem is the specification of an appropriate physical model and its associated wave equation. Next, a wave equation solution of the direct problem is obtained. This, in turn, leads to a specific description of the relationship between scattering parameters and measured quantities which, finally, must be inverted. The specification of the physical model is a crucial step in the procedure, since only those interaction parameters which are incorporated into the original wave equation can be reconstructed. However, tissue may not conform to the postulated model in all respects, and the measured data may well not be totally compatible with the original wave equation. Under these circumstances, the inversion scheme, which would be near-exact only under the hypothesis that the postulated physical model applies, produces an image which is, in some sense, incorrect, and thus hardly quantitative. We have used the term fuzzy (15,16) to describe an image which displays a particular parameter but is corrupted in an unpredictable manner by some other interaction characteristic not included in the original physical model. It is apparent that all scatter imaging techniques are highly model dependent since the reconstruction algorithm is determined by the wave equation which characterizes the medium. Thus, if the model is incorrect, even infinitely good resolution and an exact reconstruction algorithm will not obviate a fuzzy image. Much attention has been devoted to problems of resolution and problems of distortion in ultrasonic imaging, while fuzziness has been virtually unappreciated as a problem (17). This unfortunate emphasis on blind computation in the absence of accurate tissue modelling produces images which may be highly resolved while being distorted and fuzzy.

The three problems of resolution, distortion, and fuzziness are, in fact, inter-related. Consider a conventional impediography inversion procedure. The three steps involved here are measurement of back-scattered signals, deconvolution to obtain the impulse response and inversion via an "impediography equation" which relates the impedance profile to the impulse response. The actual form of the impediography equation depends on the physical model assumed. Consider a constant velocity model in which frequency-independent attenuation (propagator) and impedance fluctuations only (reflector) are assumed. The final impediogram will be fuzzy if it turns out that backscattering from absorption fluctuations (not included in the inversion scheme) are significant. If the attenuation is, in fact, frequency dependent, then the ensuing pulse distortions will ensure an incorrect impulse response, which will, in turn, ensure a resolution loss in the displayed impediogram. However, we will nonetheless indicate the following scheme even bearing in mind that there may be some cross-links between the columns:



It should be clear that physical modelling underpins the entire framework of quantitative imaging.

An interesting example is afforded by diffraction tomography. Initially, the technique was based on the lossless Helmholtz equation (velocity fluctuations only). Given the measurement of angle scattering on which the technique is based, it is clear that the original technique would give rise to a distorted and fuzzy image. However, a much more detailed analysis by Mueller (18), has revealed that diffraction tomography, while not being fuzzy, displays an image of a rather unexpected combination of interaction parameters. An appreciation of the fuzziness concept runs deep in Mueller's work, even though the idea is not formulated as above, or analyzed as a general problem of quantitative imaging.

Another interesting, and poorly addressed, problem associated with quantitative imaging is one we dub "freedom counting". The idea is easily explained by a simple example. Consider a two-dimensional velocity distribution, $c(x,y)$. The velocity field shows two degrees of (spatial) freedom, x and y . It is clear that in order to reconstruct the velocity map, measurements with two degrees of freedom will also be needed. For example, in (two-dimensional) transmission tomography a time-of-flight projection (one degree of freedom) must be measured at all angles (second degree of freedom) in order to achieve a reconstruction; in (two-dimensional) diffraction tomography, the field scattered at all angles (one degree of freedom) must be measured for all angles of incidence (second degree of freedom). In order to measure both the attenuation, $a(x,y)$, and velocity distribution, $c(x,y)$, of a given (two-dimensional) structure, it is clear that two sets of independent data, each with two degrees of freedom, will be required. The

simple expedient of freedom counting often allows a preliminary judgment as to whether an elaborate, and usually highly mathematical scheme can, in fact, reconstruct all the postulated interaction parameters within the context of the suggested data set.

Finally, to conclude, we believe that analytical and computational methods are available today to produce high resolution quantitative ultrasound images. However, the accuracy of such images are directly dependent on the exactness of the physical model assumed for tissue. In addition, the computations required to produce such images are quite extensive and will probably require the next generation of computer technology to be realistic.

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Computed Geometry from Magnetic Resonance Imagery

Ian R. Greenshields, J. Chun, F. DiMario, et al

Departments of Computer Science and Engineering, Pediatric
Neurology and Radiology, University of Connecticut,
Storrs, CT

1. Introduction

There is a substantial component of diagnostic radiology (in fact, general clinical practice) where a diagnosis is either predicated upon a geometric determination or is enhanced by knowledge of some local geometry. Examples of this so pervade the literature that an exhaustive summary is unwarranted and inappropriate to a paper of this length, so we will content ourselves with one or two general examples. Measuring angle or length from projective modalities (plain film or US) is so widespread that one standard text (Keats and Lusted¹) is devoted to terse explications of standards and variations drawn from every major system in the body; general fetometry is routine in antenatal care, and newer examples appear in the literature frequently. Frequently, a geometry-related diagnosis can be achieved quite satisfactorily from a projective modality, and hence the necessity or motivation to utilize a 3D modality (such as MR or CT) may not be indicated. However, this is not always so; obvious indications for some form of 3-space geometry include guided biopsies (e.g., those conducted concomitant to mammography). Even here we concede that rudimentary 3-space geometry (relative location, approximate size or volume) suffices in many cases, but when some form of fine-structure geometry is indicated, other (more rigorous) approaches are mandated.

Say the task at hand involves the determination of a clinical result based on *shape* (e.g., the classification of structures into normal or abnormal). In our case, one of the authors (FDM) has hypothesized that there may be a correlation between the global geometry of the jugular foramen and communicating hydrocephalus secondary to achondroplasia. Our goal is therefore to provide some quantitative sense of 'normal' and 'abnormal' in the context of the jugular foramen of the pediatric skull, and it is our contention that in so doing we must resort to the tools of differential geometry, algebraic topology and harmonic analysis on symmetric spaces. The space limitations of this paper dictate brevity of presentation, and so the remainder of the paper will concentrate on the provision of a skeletal outline of our approach. Future results in this area

(which we deferentially refer to as 'diagnostic geometry') will be more expansive both in the clinical applications and in the underlying mathematics.

2. Materials and Principles

The client clinical group comprise pediatric patients (achondroplastic and non-achondroplastic) who have been scheduled for an MR workup of the head. Typically, 10 to 15 dual-echo (SD and T2) transverse images are obtained. These span a (typical) 20cm $\times$ 15cm Volume of Interest (VOI) which is presented to the imaging group as a multisignature lattice of $(256 \times 256 \times m)$ (m in the range 10 to 15) voxels. Entities within the lattice are classified and either interpolated out to a continuous VOI (as is the case when the structure or entity is not amenable to a computed geometric representation, as in the determination of total CSF volume), or they are converted to a differentiable structure of known topology for subsequent analysis. We concern ourselves here with the latter process.

Conversion to a differentiable structure involves six basic steps:

- Image Preprocessing (noise removal)
- Cluster/Classification of VOI
- Conversion to Polyhedral Representation
- Conversion to Parametric Representation
- Conversion to Differentiable Structure

Once the differentiable structure is known, shape analysis can proceed. Step 1 (image preprocessing) is so common that we ignore it here.

3. Entity Classification

Since the image data set we acquire is multisignature, we opt for a *controlled classification schema* as the basic image interpretation method. The image I is simply some mapping from the VOI (i.e., some subset $V \subset R^3$) out to the (normalized) region $[0, 1] \times [0, 1] \subset R^2$. Then the signature distribution of I is just the 2-space histogram of I (denoted H_I), and clearly $H_I : [0, 1] \times [0, 1] \rightarrow [0, 1]$ when H_I has been normalized. The goal of the classification schema is to partition the domain of H_I (which we hereafter refer to as U) into disjoint subsets U_i whose union covers U . Then if $I : p_{xyz} \rightarrow q \in U_j \subset U$, p_{xyz} is said to be in class j . Notice that the primary goal of most classification algorithms is to partition the distribution space (U) of I (subject to some criterion of goodness), *not* the image space V itself (this being the real goal, but one secondary to the partitioning of U). For this reason, many classification algorithms perform in an unsatisfactory manner, in that the classes developed in V may not correspond to the structures one expects to find in V . For this reason, we use a controlled

classification schema, where the criteria of goodness are measured both in U and in V . The fundamental algorithm we use is a variant of the K-means² algorithm, which partitions U into convex subsets (under the l^2 metric) based on the notion of proximity of points in U to paradigmatic cluster centers $c_1, \dots, c_M$. Thus, if v_{xy} is a point in the distribution space U of I , and $c_1, \dots, c_M$ are distinct points of U (called the class centers), then v_{xy} is assigned to subset $U_n \subset U$ when $d(v_{xy}, c_n)$ is a minimum. ($d(\cdot, \cdot)$ is the l^2 metric; we will demonstrate in a later paper that the l^2 metric is the only meaningful l^p metric if convexity is an issue). The algorithm iteratively recomputes the c_i , terminating either when a convergence criterion is met, or when an iteration limit is exceeded. Clearly, algorithms such as this are highly dependent on the choice of initial class centers. Our control schema uses a data-pruning technique coupled with a relaxed crossover between the algorithm's performance over both U and V (e.g., the schema monitors the behaviour of edges in V under partitions of U) to mitigate the effects of a bad initial choice of class centers.

4. Polyhedralization

The data structures obtained after classification include a parallel image set $C : V \subset R^3 \rightarrow \{0, 1, \dots, M - 1\}$ whose 'voxels' c_{xyz} identify the class (0 to $M-1$) to which voxel $v_{xyz} \in V$ was assigned. Interclass boundaries are then developed from C , and those which are adjudged to belong (adhere in our terminology) to a target structure (e.g., a foramen) are retained. Clearly, this step is one of the most complex in the entire process, and we concede that at this stage our inference engine is populated with ad hoc rules which are 'demonstrated to work'. Ideally, we would like to construct an inference engine whose ruleset is more globally meaningful. One of our principle goals is the identification of 'anchor processes' (i.e., anatomical structures or physiologic byproducts whose geometry and signature we believe can be identified with high probability; in fact, our initial success in this area came from pelvic imagery^{3,4}). From this point in the process onwards, the original image data I can be discarded; no further knowledge of the MR signatures is needed. Voxels v_{xyz} which lie on the boundary of a target structure, are of constant z (i.e., all lie in the same image plane) and which lie on a simple closed connected curve are called *contour voxels*. Although there may be some merit in attempting to produce a differentiable surface directly from these contour voxels, we have adopted a bipartite polyhedralization process which generates two (not necessarily redundant) intermediate structures. Our first goal is to throw a polyhedral surface between the contours.

Much has been written on this (e.g., see^{5,6}), and although this may seem like a solved problem, it transpires that this is not the case. Essentially, the problem reduces to ensuring topological fidelity between the original surface and the polyhedral representation of that surface given the contours from the image. Virtually any of the standard algorithms can be demonstrated to fail under pathological (and often not-so-pathological) circumstances. Those based

on Voronoi tessellations may tessellate over holes, while those based on triangulations may develop self-intersecting surfaces. It seems apparent to us that algorithms which are to tessellate surfaces correctly must have some a priori knowledge of the topology of the surface they are working over (e.g., at least the fundamental group of the surface), but it is also clear that local knowledge of a topology (developed say as the algorithm builds the surface) may not suffice to inhibit the construction of a topologically invalid surface. Our current approach to this problem involves specifying the topology of the surface to the reconstruction algorithm *ab initio* (and for reasons to be seen later, we restrict our attention to surfaces homeomorphic to the sphere) and employing a symmetry-reduced expansion of the classical Fuchs⁵ triangulation strategy.

The Fuchs' strategy begins by building a torroidal graph G whose vertices $g_{i,j}$ correspond to an arc-related pairing between a point p_i on one contour and q_j on the other. (The surface is built up by unioning subsurfaces constructed pairwise between adjacent contours). Arcs in G are directed, and may either connect $(g_{i,j}, g_{i+1,j})$ (in which case they correspond to a triangle with components $\langle (p_i, p_{i+1}), (p_{i+1}, q_j), (q_j, p_i) \rangle$) or $(g_{i,j}, g_{i,j+1})$ with obvious corresponding triangle. Although Fuchs gives a 'safe strategy' for constructing a surface based on the development of a subgraph in G which satisfies three properties, it transpires that these properties are too weak to guarantee topological fidelity. There are in fact some $\frac{(n+m)!}{n!m!}$ potential acceptable surfaces (subgraphs) when the two contours have n and m contour points (respectively), only some of which are topologically valid (i.e., do not have self-intersections). As indicated above, no adequate local graph property can exclude these topologically invalid surfaces. However, one can show that many of these subgraphs are related under the action of permutation groups to each other (are in the same equivalence class), so that the number of candidate subgraphs one has to develop can be reduced to locating the coset leader subgraphs using the Polya Enumeration Theorem. When this has been done, each candidate subgraph can be expanded quickly in a parallel environment (we use a 4-processor transputer network) and tested for topological integrity. Only those which are topologically valid are retained for further consideration. In fact, we conjecture that a surprisingly low percentage of the total number of 'acceptable surfaces' are in fact acceptable topologically.

At the end of this procedure, we have a surface which is topologically valid (in the fact that it at least is not self-intersecting) composed of the union of triangular (planar) patches. Unfortunately, the conversion from a triangulation to a parametric representation is computationally too expensive, so we develop a secondary polyhedral structure which is constructed from the union of quadrilateral facets (and we accept the potential for a severe loss of planarity here). That the triangulation should proceed the quadrilateralization should be obvious; however, the triangulation is used in all visualization algorithms we employ, so while its validity as a geometrical structure is of questionable value to us, it is

of import in a secondary fashion. The quadrilateral structure is *pairwise regular*, in that it contains the same number of polygons between each contour. It is this structure which is used as a basis for the development of the differentiable structure. An example of such a structure is given in Figure 1; this happens to be the inferior surface of a urinary bladder; note that the apparent elongation is a display artifact.

5. Differentiable Structure

The pairwise regular polyhedron developed in the last section can be converted to a differentiable structure by associating a parametric patch (say a bicubic) with each component polygon. Any one of a number of standard approaches can be employed to accomplish this, but we impose the additional criteria that the surface so developed be *fair* with respect to the polyhedron (i.e., introduce no concavities when the data does not imply a concavity – see⁷) and be at least C^2 , since we will want to compute derivatives up to at least second partials. The union of these parametric patches constitutes a compact 2-manifold M , and we speak of the functions $g : P \subset M \rightarrow (0, 1) \times (0, 1)$ taking open sets on M to open sets in R^2 as the atlas on M . Since our primary reason for developing this differentiable structure is to quantify shape, further results on the differentiable structures are best developed in that context.

6. Shape

For meaningful comparative purposes, shape is clearly best described in terms of some numerical quantity (or set of numerical quantities). We would like our shape descriptors to be a) tunably unique to a given manifold; b) independent of the atlas describing the manifold; and c) invariant under certain rigid motions. By “tunably unique” to the manifold we mean that the descriptors should be effectively absolutely unique to the manifold (by their definition), but constructed in such a fashion as to allow easy blurring between two essentially equivalent manifolds (the notion of harmonic series expansion should be apparent here). We also clearly require invariance under certain rigid motions; that a shape descriptor be incapable of identifying the same entity simply because that entity has rotated (even slightly) is clearly untenable. We can clearly eliminate the effects of translation of the manifold by requiring that the shape descriptors be a function of some rigid object and providing a mapping between the actual manifold under consideration and the rigid object. In fact, this drops out nicely from the harmonic analysis.

It is clear from the preceeding discussion that we can restrict our attention to formulating a shape descriptor function invariant under the action of $SO(3)$ – the group of rotations in 3-space. The homogeneous space for this group is the sphere S^2 (which is left invariant under the action of $SO(3)$), and it transpires that the harmonic analysis over S^2 with respect to the representation of $SO(3)$ on the vector space of infinitely differentiable functions on S^2 gives rise to a

shape descriptor function of the form

$$f(\theta, \phi) = \sum_{(l,m)} A_m^l Y_m^l(\theta, \phi)$$

where f is some meaningful shape function (such as Gaussian curvature, mean curvature or geodesic curvature) and the Y_m^l are Associated Legendre functions. It transpires that such a formulation exhibits all of the "nice" properties stated above⁸, and we then call the set $\{A_m^l\}$ the *Spherical Shape Descriptors* of M . For M to have such a set of shape descriptors, it is clear that M must be related to S^2 (i.e., we must be able to construct a differentiable mapping between M and S^2), and this brings us to the central point of this paper, which we state without proof:

Theorem: Let M be a compact 2-manifold constructed as above, and let K be the Gaussian curvature on M . Then provided the integral of the total curvature is as below

$$\int \int_M K d\sigma = 4\pi$$

then there exists a diffeomorphism between M and S^2 and M has a rotationally-invariant shape descriptor function as above.

Proof: This is just the global Gauss-Bonnet theorem followed by the construction of a differentiable mapping between the parameter space of M and the parameter space of S^2 .

7. Acknowledgments

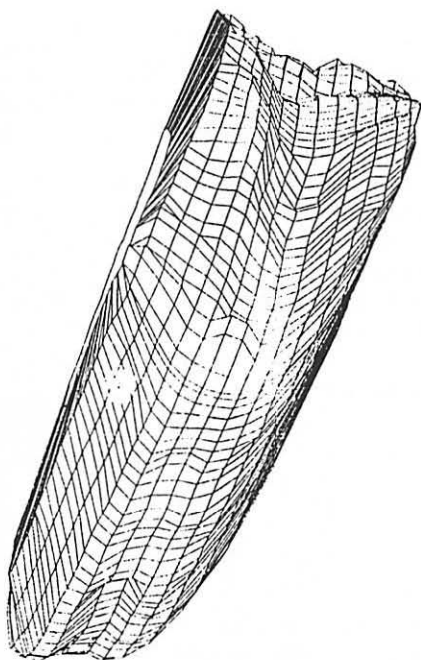
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Figure 1: Inferior Surface of Bladder



A User-Friendly Human-Computer Interface for a NMR Workstation

Gabriele von Voigt

Department of Computer Science, University College London,
London, UK

Abstract

Every computer-assisted workstation in a hospital has its own user interface. As a result, the medical staff who operate these machines have to learn a variety of systems, which are often not easy to handle and not at all self-explanatory. It is quite likely and understandable that the user has problems in operating these systems and thus mistakes are made. Would it not be advantageous to learn to handle only *one* user interface which is easy and quick to use?

The purpose of this paper is to show criteria for a user-friendly human-computer interface (HCI) for a NMR workstation and workstations from other scanner types.

The first part of this paper contains the definition of the users and an analysis of the benefits and costs of introducing the system. In the second part, one finds the user and task characteristics for a picture-oriented medical workstation, which are a consequence of a field study which examined a limited number of NMR workstations. In the third section, the author shows the derived characteristics of a general purpose HCI (GP-HCI) for medical workstations (MWS). The fourth section outlines an experimental implementation of such an interface and, in the last section, examples of specifications for tests regarding the user-friendliness are described.

Introduction

The main goal is to design a *user-friendly* system. This means, the system should be easy to operate, provide suitable functions to assist the user fulfilling his task and should be enjoyable to use. Thus the design has to be matched to the user. The presented process is based on the idea of user-centred design (HUSAT, 1989).

Section I

I.1. Understand the User

To match the design to the user, we are in an unfortunate situation, that *the* user does not exist! One suggested solution to this occurring problem is to build user-groups. These groups are formed depending on the tasks of the users. We can form the following seven user-groups:

1. Referring Physicians and Specialists such as Surgeons
2. Radiologists and Radiographers
3. Nurses
4. Administrators
5. Managers
6. Department of Health and Social Security (DHSS) Personnel
7. Patients

I.2. The Analysis of the Goals-, Benefits- and Costs

The analysis states the goals of the tasks for the user-groups, their benefits from this MWS and their costs of using or choosing this MWS. Only a system with copious benefits should be developed.

Section II

II.1. User Characteristics

The characteristics of each user-group has to be determined. These characteristics can lead directly to product requirements which we have to consider. In this paper the concentration will be on the direct user groups: radiologists (including radiographer) and physicians (including other specialists). The study which was carried out showed, for example, the following characteristics for the user-group of radiologists:

Radiologists have the following characteristics:

- * low -> medium medical knowledge
- * high intellectual ability
- * high radiological knowledge
- * low -> medium computer knowledge
- * low -> medium manual keyboard skills

Also, their work is repetitive and requires very frequent use of the system.

II.2. User Tasks

In the first step, the task environment and the working conditions have to be examined. Depending on the direct user-groups, there are mainly two areas in which the NMR workstation will be placed: one is the NMR unit based in the radiological department, which will provide adequate workspace, satisfactory lighting and it will be positioned in the surroundings with a strong magnetic field. The other environment is the ward where the workspace is normally limited, the lighting can be variable and it could be noisy.

The following product requirements can be derived:

- the size of the workstation should be small
- the brightness and contrast must be adjustable
- audible output should be avoided.

The working conditions on the ward and in the NMR unit are quite different. In the NMR unit, only a limited number of people work together with the MWS whilst creating the NMR scans. The radiologist normally handles the system and one or two other clinicians overlook it.

On the ward and especially during the presentation of the patient's record to colleagues more than one person needs to see the contents of the display of the MWS. On the other hand, the ward is a public place but the patient's data must be treated as confidential. Also, it is possible that the physician or surgeon is interrupted by a more urgent task during his work with the computer.

We can conclude the following product requirements:

- the screen must be big enough to allow for two or three users simultaneously
- the MWS must contain facilities for the visualization of the screen to multiple users
- the display needs a viewing angle limitation and a "blank screen" function
- the system needs quick store and retrieval functions

Section III

Characteristics of a general purpose HCI

1. Attractive to new users: The MWS should be a communication medium for the radiologist user group and the physician user-group. Thus, new users have to be encouraged to use the system.

2. Self-explanatory and easy to learn: The physicians are novices and they will not be interested in going through a long tutorial or in working through a handbook.

3. Easy to use including compatibility with existing system: It is easier to extend existing knowledge than to learn a totally new concept. Thus the present knowledge base should be utilized.

4. Low error rate and able to be used rapidly: The clinician will feel more confident in using the MWS if he makes no errors during the interaction. Also, every recovery of an error takes time, but in a hospital the time which he can spend with the computer is limited.

5. Interruptable and easy to resume after an interruption: Earlier, the task analysis showed that the physician might be interrupted during his work with the MWS. Afterwards he will want to restart at the point where he stopped.

6. Relieving the user's memory load: Interaction sequences and previously worked out commands should not be required again by the physician or radiologist.

7. Laid out consistently: The necessary interaction should be easy to remember. To achieve that end, the clinician must be able to create a mental model of the system. Therefore, one philosophy should guide the physician or radiologist through the interactions, even if both user-groups are quite different.

8. Providing quick response to frequent users and providing prompts to remind infrequent users: Whereas the radiologists are frequent users, the physicians are infrequent users.

9. Supplying information as requested and not insulting the intelligence: The designer also has to pay attention to the intelligence of both user-groups.

10. Supportive in the search for a particular patient folder: Both user-groups have in common that one of their basic and frequently used functions is the storing and retrieval of a particular patient folder.

11. Able to present different patient data in a uniform way: They are familiar with the concept of a patient folder and to the information being presented in a uniform way. A fever curve has to be displayed as a curve, if this is the usual method, and not as an array of measurements.

12. Able to display 3D image data: All natural objects are three dimensional. Thus we are used to understand an object in three dimensions. It seems obvious to the author that patient data which contains 3D information, like NMR scans, should be displayed as a three dimensional object as well as in two dimensions.

13. Supportive in interacting with the 3D image data: That requires interaction devices which allow the handling, the operating with and the manipulation of three dimensional information.

14. Using highlighting and pseudo colour for important items: The patient data, together with the necessary interaction information presents a great amount of information which has to be displayed. Therefore, a good use of colour can help to give an emphasis on special objects.

15. Using the human sensibility of motion: Also, the human eye is sensible to motion. A good designer will use these and other ergonomics for his layout.

16. Indicating the needed time for the execution of an operation: If a computer function needs some time to calculate the results, it is essential that the user gets an estimate of the execution time.

17. Indicating the state of the system and supportive in the orientation throughout the system: The MWS should make it always clear, in which state it is. The feedback is necessary for the clinician to judge if the computer action fits his expectations. It is important that he never loses his orientation whilst working with the system

18. High reliability: System crashes are not permissible.

19. Secure - as required by the Data Protection Act: In the hospital, we have constraints due to the Data Protection Act. Therefore, during the interaction, we have to prevent anyone overlooking the physician's work and the MWS must be secure against unauthorized access.

20. Challenging and enjoyable to use: Last but not least, the use of the MWS should be challenging and enjoyable.

Section IV

IV.1. Design of the GP-HCI

This section outlines a possible design of a general purpose HCI for a MWS regarding the two direct user-groups. There are mainly three areas of interest, which will be explained in the following.

IV.2. Style of Interaction

The suggested design has the four most important features:

- * user-guided dialogue
- * direct manipulation
- * flexible menus and icons
- * pre-stored values

The dialogue should be *user-guided* to give the clinician more control and flexibility. If an entry for a new patient in the database has to be made, the entering of the data should be done by using form-filling dialogue method. All other data entry will be supported by *direct manipulation*. The user's commands, decisions and option choosing will be supported by *flexible menus*. This assists the human hierarchical memory structure and process of choice. If the choices can be shown graphically, the use of *icons* should be considered. For frequent inquiries, *pre-stored values* should be available. These can be defined as macros with their own icons.

IV.3. Appearance

The two following features characterize the design:

- * multiple windows
- * graphics and alpha-numerical data

The screen is laid out by using *fixed and overlapping windows* which are under user control. A fixed menu in the top of the screen shows all main choices of the MWS continually. In this way the major part of the screen is available for displaying the relevant data at any time, and the user still has an overview of the main features of the whole system. The additional options relating to the main choices are hidden in *pull down menus*, thus the screen remains uncluttered. *Graphical and alpha-numerical data* can be visualized. The most relevant data should always be presented in the middle of the screen.

IV.4. Input

The input will be assisted by the following:

- * function keys, 2D and 3D mouse
- * help button

Function keys can be used if the interaction is rapid and the information is simple or context free. The *2D mouse* is suitable for the flexible menu approach and the *3D mouse* stands for all appropriate 3D input devices which allow the easy handling of 3D patient data. Context sensitive help should be always available by using the *help button*.

Section V

Test specification

Having a prototype, tests have to be done which show if the characteristics outlined in section III are fulfilled. As an example, the specification of the tests for two of the characteristics will be shown.

Test 1 shows if the MWS is *self-explanatory*:

Test procedure: laboratory test with and without tutorial

Measure: time to complete given tasks

data collection: observation, on line timing, questionnaire

One group of users uses the MWS prototype with and another group without a tutorial or handbook. We measure the time they need to complete several set tasks. We should also observe how they handle the MWS and ask them afterwards about their difficulties.

Test 2 can tell us if the use of the MWS is *challenging and enjoyable*:

Test procedure: prototype in area for casual use

Measure: count users, collect their comments

data collection: data record, questionnaire

We place a prototype in an area which is accessible for casual users. We count how many users approach the MWS, what they do and how many tasks they solve and we ask them about their criticisms. To achieve this, we create automatically a data record and let the users fill in a questionnaire.

Conclusion

The user interface plays a very important role for the acceptance of a medical workstation. The author suggests to facilitate the idea of user-centred design for the design process. After characterizing the users and tasks, product requirements can be derived. Then a prototype can be built and tested. These tests may lead to re-design of parts or in the whole as appropriate.

This paper can only present some of the necessary requirements, but could help other interested parties. The design of a GP-HCI in this area is a great challenge and, in the eyes of the author, a step in the right direction.

Reference

HUSAT: *Tools for User Centred Design*, HUFIT Seminar, Loughborough University of Technology, Leicestershire U.K., 10-13 October 1989

Personal Computer Analysis of Population-Specific Fetal Growth Patterns Observed on Obstetric Sonograms

H. Richard Parvey

Department of Radiology, Louisiana State University Medical Center,
Shreveport, LA

INTRODUCTION

Gestational age (GA) and fetal weight (FW) are often estimated by comparing sonographic measurements of the fetal body and head to standard values in published tables or charts. Ideally, the standards used to analyze a given patient's fetal measurements should be derived from the same population as that of the patient. Unfortunately, the "standard" charts and equations commonly used are often based upon a different population that may exhibit a quite dissimilar fetal growth pattern; calculations of both GA and FW could therefore be in serious error.

Developing a fetal growth standard from one's own patient population is more advantageous, but requires the manipulation and intricate analysis of large volumes of numerical data. Such a "population-specific" reference can be developed, however, using inexpensive software with an IBM-compatible personal computer (PC). The PC can also be used to analyze trends of fetal growth within a particular population.

MATERIALS AND METHODS

Patient data is recorded into a spreadsheet ("Quattro", Borland International, Scotts Valley, CA). A non-relational database ("Q&A", Symantec, Cupertino, CA) facilitates patient follow-up. IBM-compatible PC's with a 80286-based central processing unit, a 20 MB hard drive, and

either 512KB or 1024KB of random access memory are used. Both Quattro and Q&A include routines by which data can be easily imported or exported between the two.

Data acquisition involves several steps:

1. A Quattro spreadsheet file is designed with each row representing a data-base record for a single ultrasonic examination on a given patient. Each spreadsheet column represents a data-base field (Patient Name, Date of Exam, etc.). A corresponding Q&A data base file including several of these same fields is also designed.

2. At the time of the sonogram, the patient's name, age, hospital chart number, date of the sonogram ("Date of Exam"), fetal biparietal diameter (BPD), head circumference (HC), abdominal circumference (AC), and femur length (FL) are each entered in a separate spreadsheet cell. Menstrual age (MA) at the time of examination ("MA by Exam") is estimated according to the method of Hadlock et al¹ and is entered in another cell. The expected date of confinement is calculated and entered into still another cell ("EDC by Exam") using the formula:

$$(\text{Date of Exam}) - (\text{MA by Exam} \times 7) + 280.$$

3. Each new line in the spreadsheet is then imported into a data base record in a Q&A file. Additional Boolean fields in each Q&A record indicate whether the mother's delivery date has been established ("Delivery Follow-Up?") and whether the baby's hospital chart has been reviewed ("Baby Follow-Up?"); "No" is initially entered in both of these. A character field is reserved for the baby's hospital chart number.

4. At regular intervals thereafter, the Q&A data base is searched for those mothers who should have delivered by the time of review. Records are retrieved by utilizing "EDC by Exam <= (selected date)" and "Delivery Follow-Up?" = "No" as search criteria. A columnated report is then printed listing the patient names and hospital numbers for these retrieved records. This list is then given to medical records

personnel so that the mothers' medical charts can be obtained.

5. The mother's chart is reviewed. Patients with twins or with such conditions as chronic hypertension are deleted. The actual date of delivery for acceptable patients is recorded in the appropriate spreadsheet row. The baby's hospital number is obtained either from the mother's hospital chart or from neonatal nursery records. If all these data are available, then the baby's hospital number is entered into the appropriate field of the Q&A data base record and "Yes" is entered in the field "Delivery Follow-Up?".

6. The Q&A data base is then searched for those mothers whose birth records have been reviewed but whose babies' records have not. These records are retrieved by using the search criteria "Delivery Follow-Up?" = "Yes" and "Baby Follow-Up?" = "No". A second columnated report form is printed with the names of the mothers and the chart numbers of the respective infants. This list is then given to medical records personnel and the infants' hospital records are obtained and reviewed. Infants with low Apgar scores (less than 7 at five minutes), prematurity, low birth weight, etc., are first deleted. Weight, crown-heel length, and head circumference at birth are then recorded. "Actual gestational age at birth" is estimated by a modified Dubowitz score². If a specific Dubowitz score is not listed but the infant is felt to be "term", an "actual gestational age" of 40 weeks is assigned.

7. The above data are all entered into the respective cells on the appropriate row of the original Quattro spreadsheet. Actual menstrual age at the time of initial sonographic examination ("Actual MA at Exam") is then retrospectively calculated using the formula:

Actual MA at Exam

$$= (\text{Actual gestational age at birth}) - \\ - \{ (\text{Actual Date of Delivery}) \\ - (\text{Date of Exam}) \} / 7.$$

The completed spreadsheet rows are then moved into another identically designed spreadsheet file entitled "Complete".

RESULTS

The "Complete" spreadsheet file presently includes the data from approximately 600 obstetric examinations performed at the Louisiana State Medical Center in Shreveport. This "Complete" file can be sorted and re-edited to produce a spreadsheet in which the column "Actual MA at Exam" represents the independent variable and the column for each fetal parameter (BPD, HC, AC, or FL) represents a dependent variable. In this way, one can produce graphs (Fig. 1) or tables representing a standard reference for a population's fetal growth during gestation. Data from other institutions can be imported into and graphed from the same spreadsheet so that different patient populations can be compared (Fig. 1).

The spreadsheet data can also be used to determine statistically valid and population-specific regression equations for directly estimating gestational age at the time of a sonogram from fetal measurements. To this end, BPD, HC, AC, or FL are considered as independent variables and MA as a dependent variable. Establishing such regression formulae is greatly facilitated by saving the spreadsheet file in a "Lotus-compatible", ASCII or comparable standard format so that data can be readily exported to other statistical or graphics programs. Our regression formulae will be the subject of a future report.

One can also analyze errors in gestational age determination. In this case, a new column entitled "Error" is inserted. Values in this column are determined by the formula:

$$(\text{Actual MA at Exam}) - (\text{MA by Exam}).$$

This value can be then plotted as a function of Actual MA (Fig. 2).

Figure 1. Growth of abdominal circumference (AC) during gestation in LSU-Shreveport patients compared to mean AC in those studied by Hadlock et al¹. LSU patients demonstrate a relative deceleration of growth after approximately 32 weeks. Graphs for BPD, HC, and FL showed similar though less pronounced "drop-offs".

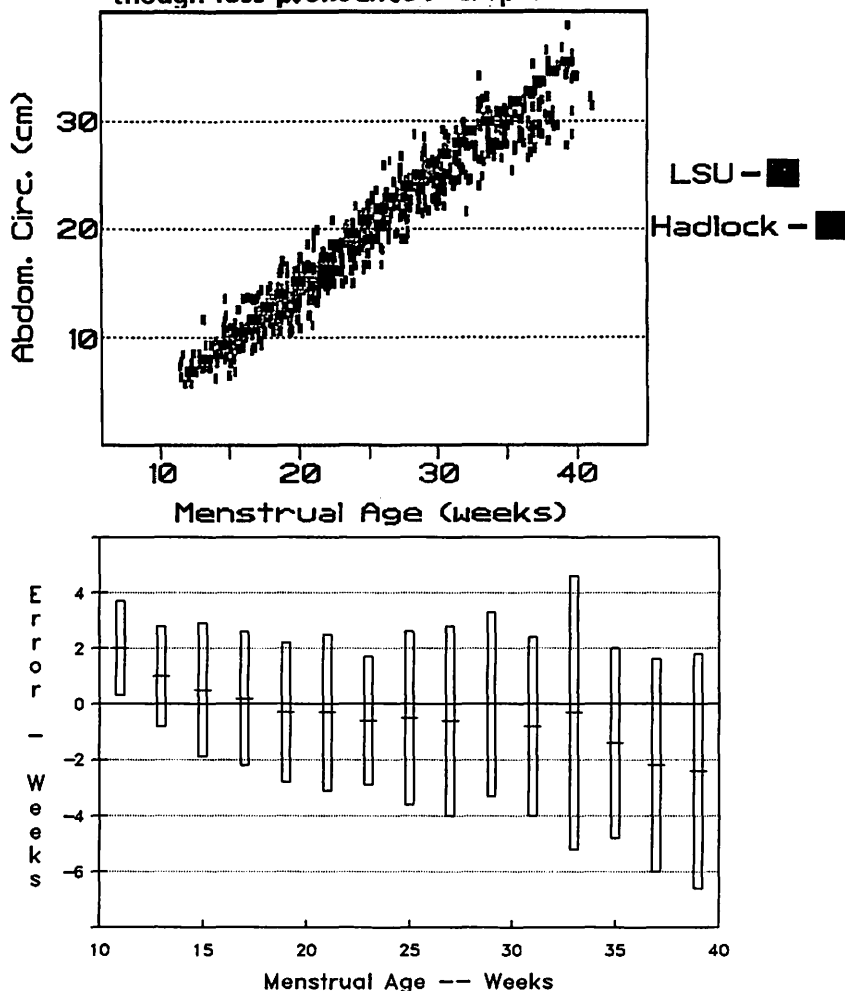


Figure 2. Menstrual age (MA) error (mean $\pm$ 2 SD) as a function of duration of pregnancy. Error = (MA predicted by sonogram from Hadlock standard¹) - (actual MA at time of ultrasound as computed from post-natal gestational age). Note increasingly negative values during the third trimester.

DISCUSSION

A "standard" gestational age chart derived from one patient population may not be applicable another because of differences between the two groups' fetal growth rates. Our patients' BPD, HC, FL, and particularly their AC did tend to be smaller, particularly after 32 weeks, than those of the population used by Hadlock et al¹ to derive one of the more widely used standards (Fig. 1). As a result, our patients' MA during the later stages of pregnancy was underestimated by up to 2-3 weeks (Fig. 2). This discrepancy can have obvious implications for patients with such conditions as diabetes mellitus or intrauterine growth retardation in whom accurately timed early delivery may be necessary to enhance infant survival. The PC approach described herein can, however, provide a relatively simple way to define a fetal growth chart that is more apropos for one's own clinic. The PC can also help test this new population-specific standard; for example, another spreadsheet can be designed where the expected date of confinement predicted by the new chart is compared with the actual date of delivery.

It is conceivable that the apparent differences between our population and that of Hadlock et al¹ are due more to dissimilar methodology than to dissimilar patient populations. The "gold standard" of gestational age for most fetal growth references, including that of Hadlock et al¹, is defined prospectively by the first day of the patient's last normal menstrual period (LMP), while our "Actual MA at Exam" is computed retrospectively from the infant's gestational age at birth. Both methods may still provide similar results³; moreover, the retrospective method, unlike the prospective one, eliminates the bias produced by excluding women with uncertain or unreliable dates⁴. Nevertheless, these methodological discrepancies do not in themselves detract from the use of a PC to evaluate fetal growth

trends. A spreadsheet file can be designed in which "Date of LMP" can be entered in a date cell; time since that date can then be easily computed and placed in another cell or column (e.g., "Menstrual Age from LMP") and then quantitatively compared with the "Actual MA at Exam" determined retrospectively from Dubowitz scores.

The PC is also sufficiently flexible to support undertakings beyond the derivation of a population-specific fetal growth chart. Any variable or quantity that can be sorted or searched in a database or calculated in a spreadsheet can be investigated. For example, maternal parity, weight, or smoking history can be recorded and correlated with changes in BPD, etc., during gestation. Data can be exchanged between different computers, researchers, and programs. Additionally, data files can be easily transmitted via modem to colleagues in distant cities. The procedures described in this paper serve only as a suggestion; the actual possibilities and applications of the PC are limited only by one's imagination.

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Monte Carlo Simulation and Glandular Tissue Doses in Mammography

Xizeng Wu, Gary T. Barnes and Douglas M. Tucker

Departments of Radiology and Biomedical Engineering,
University of Alabama at Birmingham, Birmingham, AL

ABSTRACT

Average glandular tissue dose in mammography is generally determined from published tables with knowledge of the breast entrance skin exposure, beam quality (HVL), breast thickness and breast composition. Utilizing a carefully benchmarked Monte Carlo simulation we have found that, for commonly employed molybdenum target/molybdenum filter source assemblies, average glandular dose also depends on x-ray tube voltage. For the same HVL errors of 10% or more possible in estimating average glandular dose if the x-ray spectrum employed is different from the one used to develop the reference dose table.

INTRODUCTION

Established computer applications in radiology include radiation therapy treatment planning, billing, CT and radiology information management, and MRI. More recently PACS and teleradiology, Computed Radiography, and 2D and 3D image processing have been introduced. In addition, there are a number of other less visible but fundamental applications. Monte Carlo simulation and modeling of the x-ray interactions in tissue is one of such example. In this paper, a Monte Carlo simulation of photon transport in breast tissue and the associated absorbed dose is presented.

At present, mammography is the most accurate and reliable means of detecting minimal, non-palpable breast cancers^[1,2]. However, the carcinogenic risk associated with the absorbed radiation dose to the breast, and in particular glandular breast tissue, is of concern and mammography doses are routinely monitored^[3]. If the normalized average glandular dose D_{gN} (the average glandular dose per unit entrance skin exposure) is known,

the average glandular dose D_g can be computed from the product of D_{gN} and the breast entrance skin exposure X_{ESE} . That is,

$$D_g = D_{gN} \cdot X_{ESE} \quad (1)$$

where the respective units of D_g , X_{ESE} and D_{gN} are rad, roentgen (R) and rad/R.

The evaluation of the glandular dose delivered in a mammography exam is thus reduced to a measurement of the breast Entrance Skin Exposure (ESE) and an evaluation of the normalized average glandular dose D_{gN} , which is generally assumed to be a function of beam quality (HVL), x-ray tube target material, breast thickness and breast composition. Utilizing these assumptions D_{gN} has been studied experimentally^[4,5] and with Monte Carlo simulations^[6,7]. Based on these studies, the U.S. Food and Drug Administration and National Council on Radiation Protection and Measurements have published tables of D_{gN} as a function of beam HVL, x-ray tube target material, breast thickness and breast composition^[7,8]. These tables assume that the incident x-ray spectrum is adequately characterized by HVL and x-ray tube target material. Additional factors such as x-ray tube voltage, voltage waveform and beam filtration which are necessary to properly characterize an x-ray spectrum are not addressed. In this paper we show that tube potential is an important consideration.

METHODOLOGY

X-ray photon transport is a stochastic phenomenon, and Monte Carlo techniques simulate this process^[9]. By using random numbers, i.e., by "throwing a dice", this technique performs sampling experiments on photon-tissue interactions by tracing the histories of individual photons. Macroscopic behavior is obtained by averaging the results of repeated experiments. For example, if D_i is the dose delivered by the i th photon to tissue and N photon histories are traced, then the average dose per photon is

$$D_{ave} = (\sum D_i)/N \quad (2)$$

Since each X-ray photon interaction in tissue is independent, the central limit theorem guarantees that the dose thus found will be a good approximation of the true dose as long as the total number of photon

histories traced is sufficiently large. In our simulation 1 million photon histories were traced per run, and the relative error of D_{ave} is less than 1%.

In mammography there are three physical processes of interest — photoelectric absorption, incoherent scattering and coherent scattering. The quality of a Monte Carlo simulation also depends on the accuracy with which these processes are described. Care was taken in this step. Interaction sites were sampled by using the total attenuation coefficients of breast tissue, and the interaction types were sampled by using the photon cross section data for the three physical processes involved in mammography. For coherent and incoherent scattering electron-binding effects were taken into account by employing the appropriate atomic form factor (coherent) and scattering function (incoherent). The photon cross sections, form factors and scattering functions employed were obtained from the Evaluated Nuclear Data File (ENDF)^[10].

The details of Monte Carlo simulations of x-ray photon transport have been described in the literature^[9]. Our simulations utilized a modified MCNP code^[11]. Modifications were made to adapt the source code so that it runs under the UNICOS operating system (it was written originally to run under COS operating system of Cray supercomputers). Other source code modifications were made so that the primary and scatter interactions could be monitored, since this information is of interest in mammography. Also, in order to use the MCNP package to determine normalized glandular breast dose, command files were designed so that the photon energy, geometry, photon cross sections and energy deposition were appropriately treated to simulate the problem of interest.

The breast was assumed to have a semi-elliptical cylindrical shape (semi-axes 9 cm and 8 cm) with a uniformly distributed mixture of glandular tissue and adipose tissue contained within a 0.4 cm thick skin layer. The chest wall dimension was 18 cm and the chest wall-to-nipple dimension 8 cm. This shape is representative of a typical compressed breast for the craniocaudal projection and is the same as that employed to develop the FDA's dosimetry tables^[7]. In the simulation, a range of breast compositions and breast thicknesses were studied. The elemental composition of the glandular and adipose tissues were taken from the measured results of Hammerstein, et al^[4].

Normalized average glandular doses were computed as described above at 28 energies ranging from 7.5 keV to 34.5 keV with a energy

resolution of 1 keV. Polychromatic normalized average glandular doses were calculated by appropriately weighting the monoenergetic results. The x-ray spectra used in the computation were obtained employing the constant potential molybdenum target, molybdenum filter x-ray spectra model of Tucker, Barnes and Wu^[12] and ranged in x-ray tube potential from 25 kVp to 35 kVp. At a given tube potential different HVLs were obtained by varying the thickness of polycarbonate plastic (i.e., compression paddle thickness) placed in the beam.

Prior to computing the average glandular doses, a number of checks were run and the predictions of our simulation were compared with the 32 kVp scatter-to-primary ratio measurements of Barnes and Brezovich^[13] and depth dose measurements of Hammerstein, et al^[4].

Table 1. Comparison of measured and computed scatter-to-primary ratio for 6 cm thick circular Lucite phantom

Field Diameter (cm)	Scatter-to-Primary	
	Measured	Computed
4	0.54	0.50
6	0.65	0.63
10	0.80	0.79
14	0.86	0.86

RESULTS

Compared in Table 1 are the scatter-to-primary measured by Barnes and Brezovich and the computed values for a 6 cm Lucite phantom and different field sizes. The agreement between the two is excellent. Good agreement (1-5%) was also obtained between the depth dose measurements of Hammerstein, et al and the computed values.

A paper containing a comprehensive tabulation of our calculation of normalized average glandular doses for different breast thicknesses, compositions, tube potentials and HVLs has been submitted for publication^[14]. Results from this tabulation for a 50% glandular - 50%

adipose 5 cm breast are listed in Table 2 for tube potentials of 25, 30 and 35 kVp and 0 and 3.5 mm of Lexan added to the beam. The latter is typical of the maximum thickness of compression paddles on state-of-the-art mammography units. Of interest is that for a given HVL, D_{gN} increases with increasing kVp.

Table 2. Computed normalized average glandular dose (rad/R) for 50% glandular - 50% fat 5 cm breast

Tube Potential (kVp)	Lexan Thickness (mm)	HVL (mm of Al)	D_{gN} (rad/R)
25	0	0.266	114
	3.5	0.331	138
30	0	0.306	135
	3.5	0.374	160
35	0	0.332	149
	3.5	0.400	173

Table 3. Normalized average glandular doses for molybdenum target source assembly interpolated from FDA tabulation

HVL (mm of Al)	D_{gN} (rad/R)
0.26	126
0.28	133
0.30	140
0.32	147
0.34	154
0.36	161

DISCUSSION

The agreement between our computed scatter-to-primary and depth dose values and experimental measurements gives us a high degree of confidence in our Monte Carlo simulation techniques and in our normalized average glandular dose results. For comparison Table 3 list values for a molybdenum target x-ray tube that were extrapolated from the FDA tabulation. For a given HVL, these values agree quite well with our 35 kVp results. However, they are 10% greater than our 25 kVp results. Tube potentials of from 25 to 28 kVp are commonly used in mammography. At these potentials our results indicate that the breast doses calculated with the FDA tabulation typically over estimates the dose from 5 to 10%.

Our results include the effect of x-ray tube potential and are therefore an improvement on the accuracy with which one can calculate average glandular dose in mammography. Our strategy in computing the average glandular dose is different in several respects from the earlier work of Rosenstein and Warner^[6] on which the FDA average glandular dose tables are based. First, they neglected to take into account the coherent scattering and electron-binding effects for coherent and incoherent scattering in their simulation. These effects could result in errors of up to 20% for the depth dose, and 5% for D_{gN} . Second, Rosenstein and Warner's computations utilized coarse energy resolution — 7 photon energies ranging from 10 keV to 55 keV compared to 28 energies ranging from 7.5 keV to 34.5 keV. Third, Rosenstein and Warner did not employ spectra that are consistent with modern clinical practice. They were interested in a wider range of beam qualities than are currently employed in screen-film mammography. As a result their compilation provides an average estimate of D_{gN} for a given HVL for molybdenum target, glass window and molybdenum-tungsten alloy, beryllium window source assemblies with different added filtrations and tube potentials. The spectra we employed are consistent with state-of-the-art screen-film mammography.

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FROC Evaluation of Workstations

Dev P. Chakraborty

Department of Radiology, Hospital of the University of Pennsylvania,
Philadelphia, PA

1. INTRODUCTION

Video display technology is recognized as the limiting step in the imaging chain of a workstation. Measurement of the image quality of video displays therefore deserves further attention. One approach is to measure the physical characteristics of the monitor with, for example, photometric measurements^{1,2}. Unfortunately, this type of measurement does not allow for perceptual issues involved in diagnosis. Another approach is to use test patterns (e.g., SMPTE test pattern³) and determine, for example, the limiting resolution of the monitor. This type of test is subjective and difficult to quantify; furthermore, no consideration is given to the observer's confidence level or the false positive problem.

Receiver Operating Characteristic (ROC) methodology has been used to measure the efficiency of human observers viewing video displays⁴. This type of measurement could, in principle, be used to quantify the performance of displays. However, these ROC experiments are quite cumbersome to perform, needing many images to build up acceptable statistical precision.

An alternate type of observer performance experiment, the Free-response Receiver Operating Characteristic (FROC) experiment, has recently been studied^{5,6,7}. Unlike the ROC experiment which must ignore the location information in detection/location experiments, and are limited to experiments with 0 or 1 abnormality per image, the FROC experiment requires correct location for a true positive event, and allows for multiple signals and observer responses per image. It is recognized that FROC methodology is intrinsically capable of better statistical precision for a

given number of images than ROC. In this study we present preliminary FROC measurements which extract an index of performance to good accuracy using relatively few images. We also suggest a new way of objectively evaluating the image quality of displays.

2. METHODS

We employed a Virtual Imaging workstation (VI-2000) with a 1280 x 1024 x 8 bits display for the experiments. We generated images consisting of signals (discs of 4 pixel radius, or dots of 1 pixel) embedded in noise using a computer and a random number generator. Each image contained 5-12 non-overlapping signals, and typically 30 to 60 images were generated. The pixel values inside the signal were generated from a gaussian distribution with mean μ_s and standard deviation σ gray scale units (gsu), while the pixel values outside the discs were generated from a gaussian distribution with mean μ_n (=110 gsu) and standard deviation σ . Values used for $\Delta\mu$ ($\equiv \mu_s - \mu_n$) and σ are tabulated in the table. Neglecting MTF effects, the Signal to Noise Ratio (SNR) is given by

$$\text{SNR} = \frac{\Delta\mu}{\sigma} \sqrt{n} \quad \text{Eq. 1}$$

where n is the total number of pixels associated with each object ($n=49$ for the discs, and $n=1$ for the dots). Two observers were used for this preliminary study. They interacted with the images using a 'mouse' to move a pointer on the screen. They indicated perceived signal objects (discs or dots) by moving the pointer to the center of the object and clicking the 'mouse' button. The computer then drew a box around the indicated position. At the end of each image the observers had the option to see the locations of all signal objects present in the image (feedback). Data was collected in the Free-response Forced Error (FFE) manner⁷, i.e., the observer did not indicate confidence levels but instead indicated the most likely disc location first, followed by the next most likely one, and so on. The computer kept a record of all responses, and determined that the observer had made a false positive error before allowing him to move on to the next image (actually, to allow flexibility in subsequent analysis, we required the observers to make three false positive errors on each image).

The response data was analyzed in the following manner. The criterion for a true positive was arbitrarily set at a 6 pixel maximum separation between the coordinates of the center of an object and the coordinates indicated by the reader. The analysis consisted of counting the number of hits before the first false positive, and dividing by the number of signals present in the image. This is an estimate of the FROC area parameter for that image (A_1^i). Averaging the A_1^i over all images yields A_1 for the image set. The standard deviation is calculated in the usual manner, namely the standard deviation of the A_1^i divided by the square root of the number of images.

3. DISCUSSION

The table summarizes the results of this study. The column under 'Contrast' refers to whether or not the observers were allowed to use the window and level controls to optimize the display. The column under A_1 lists the FROC index (which can take on values in the range 0.0 to 1.0, unlike the ROC index which ranges from 0.5 to 1.0) and the corresponding standard deviation. It is seen that when the noise level σ is decreased, while maintaining a constant SNR, the performance of the observers decreases. This is consistent with the noise introduced by the display becoming more of a limitation than the intrinsic (computer generated) noise level of the pixels. This suggests a way to measure the display noise as discussed below.

It is seen from the table that the standard deviation of the FROC index is typically 6 to 9% of the A_1 value. It should be borne in mind that these are derived from as few as 30 images. The standard deviations can be reduced further by using more images, but the number of images needed is still much smaller than that needed in studies using ROC experiments. This is because the FROC experiment utilizes information (location data, and multiple response data) that ROC analysis is forced to discard.

The preliminary measurements described here suggest a strategy to measure the image quality of displays: we construct 'calibration' images at different SNR's, where the σ values are intentionally chosen to be large ($\Delta\mu$ should be correspondingly large), so that display noise is not a limitation. Measuring the performance of an observer over these images yields an empirical 'calibration' curve for the observer, i.e., a plot of A_1 vs. SNR (Fig. 1). Next we prepare a test set of images for which $\sigma = 0$, so that any noise introduced is due to the display. By selecting $\Delta\mu$ appropriately, perhaps a few grey levels, one can arrange to have the signals neither too obvious nor too difficult. Measuring the performance of the observer using the $\sigma = 0$ image set and using the calibration curve, we can convert the measured $A_1(0)$ to an effective Signal to Noise Ratio, $SNR(0)$, as depicted in Fig. 1. It can be seen that, to first order, variability in observers cancels out when $SNR(0)$ is calculated in this manner. A 'better' observer will yield higher A_1 values than a 'poorer' observer, but the $SNR(0)$ for each will be the same because they will each have a unique calibration curve.

The $SNR(0)$ can be converted to an equivalent noise, σ_{eq} , by inverting Eq. 1, i.e.,

$$\sigma_{eq} = \frac{\Delta\mu(0)}{SNR(0)} \sqrt{n} \quad \text{Eq. 2}$$

The equivalent noise can be thought of as that computer generated noise on a perfect display that yields the same performance for a given reader as the actual display noise. The equivalent noise can be related to a noise-power spectrum to normalize dependences on pixel dimensions, etc. The noise measurement could be repeated for different size discs/dots, and at different average grey-scale levels, to more fully characterize the display. Obvious applications of the methodology suggested in this paper would be to evaluating the newer high resolution displays that are becoming available. Finally, we note that the method need not be restricted to video displays and could be applied, with few modifications, to evaluating digital harcopy devices.

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5. TABLE: SUMMARY OF RESULTS

Obj.	$\mu_s - \mu_n$	σ	SNR	Cont. Read.		A ₁ (s.d.)
Disk	20	25	5.60	Yes	A	0.589 (0.033)
Disk	20	25	5.60	Yes	B	0.559 (0.036)
Disk	4	5	5.60	No	A	0.353 (0.032)
Disk	4	5	5.60	No	B	0.436 (0.036)
Dot	18	3	6.00	No	A	0.671 (0.038)
Dot	18	3	6.00	No	B	0.553 (0.040)

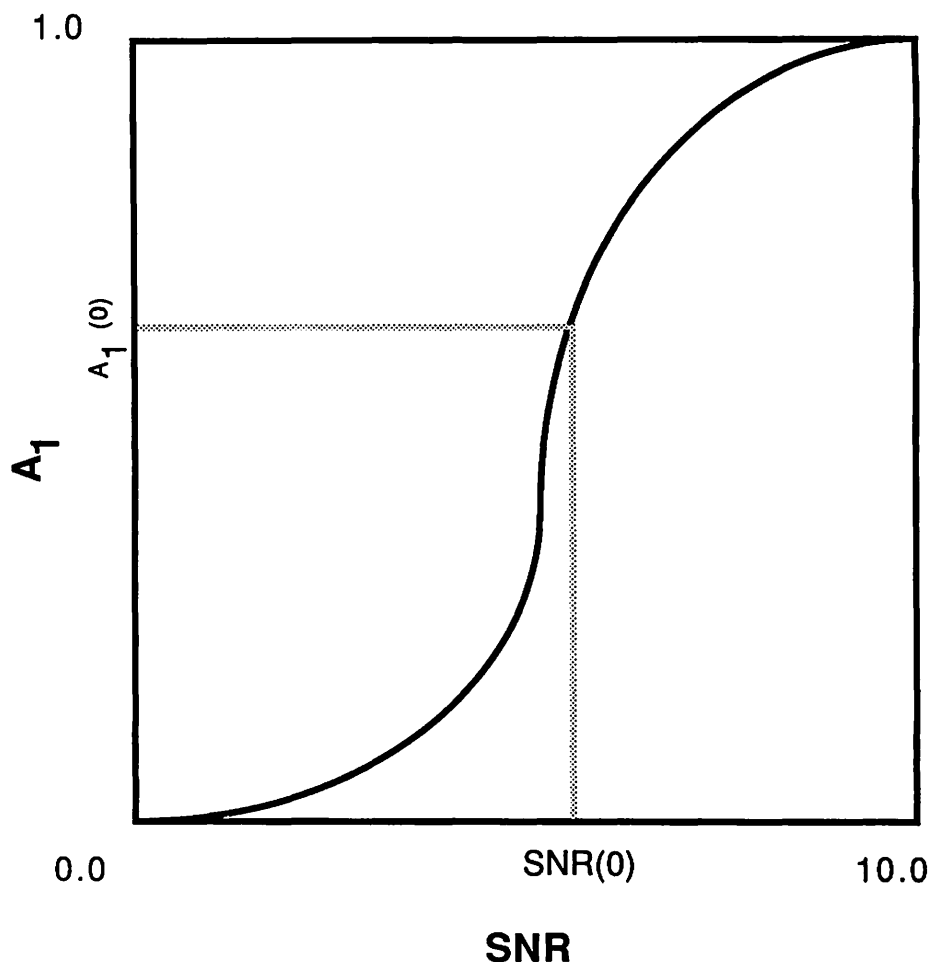


Fig. 1. Illustrating the proposed method for measuring display noise. The curve sketched is a 'calibration' curve for an observer measured empirically. It is measured in the large computer generated noise limit (so that display noise is not a limitation). $A_1(0)$ is measured with zero computer generated noise, so that any noise introduced is due to the display. $SNR(0)$ can be converted to an effective display noise as explained in the text.

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